

sPHENIX TPC: Further Details

TK Hemmick



Next Generation TPC Concept

- ▶ Traditionally TPCs are considered as slow devices:
 - ▶ Long time to drift the primary electrons to the gain stage.
 - ▶ LONGER time to dump the positive ions down the drain.
 - ▶ Operation cycle:
 - ▶ “Gate” is closed preventing positive ion back flow and electron drift to avalanche stage.
 - ▶ Trigger causes gate to open for period necessary to collect electrons.
 - ▶ Gate closes for period necessary to reject ions.
 - ▶ Device ready for next event.
- ▶ New concepts coming out of ALICE and STAR experience.
 - ▶ “Stacked” events are not so big problem (STAR and ALICE):
 - ▶ Independent event vertex.
 - ▶ Confirmation by “fast detector” or at least “different” detector.
 - ▶ Ion field distortion is a “manageable” correction (STAR)
 - ▶ New device (ALICE):
 - ▶ Gate-less design using gain stage w/ intrinsically low Ion Back Flow (IBF).
 - ▶ Continuous readout electronics (define event boundaries offline).

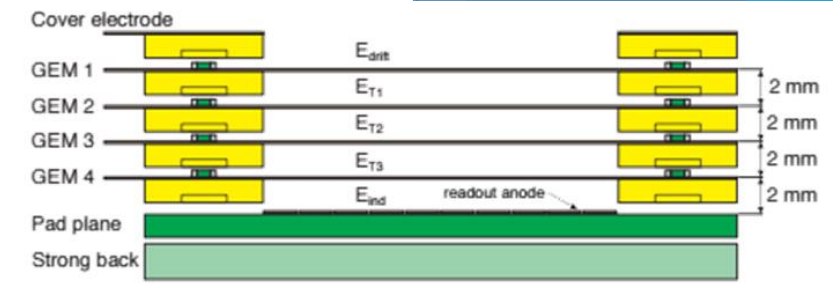


Figure 4.6: Schematic exploded cross section of the GEM stack. Each GEM foil is glued onto a 2 mm thick support frame defining the gap. The designations of the GEM foils and electric fields used in this TDR are also given. E_{drift} corresponds to the drift field, E_{Ti} denote the transfer fields between GEM foils, and E_{ind} the induction field between the fourth GEM and the pad plane. The readout anode (see Eq. (4.2)) is indicated as well. The drift cathode is defined by the drift electrode not shown on this schematic.

Micro Pattern Gas Detector

SAMPA Chip

Positive Ion Mobility: Limit Space Charge w/ Fast Ions

- ▶ This challenges one's belief in silver linings!
- ▶ I know of no good that comes from positive ions in the drift volume.
- ▶ The ion mobility itself is easy to calculate:
 - ▶ Independent of field for all reasonable E_{drift}

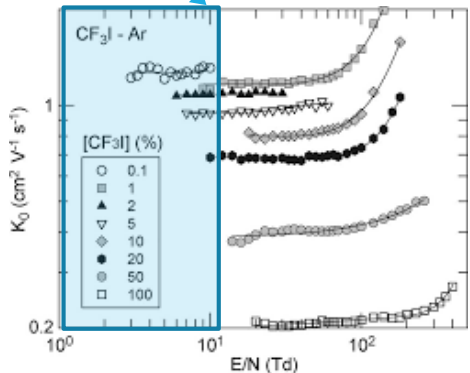
$$v_{\text{ion drift}} = KE$$

- ▶ Easy to calculate for gas mixtures

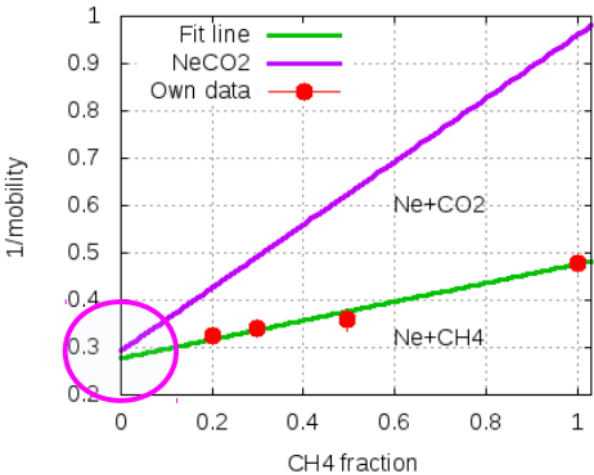
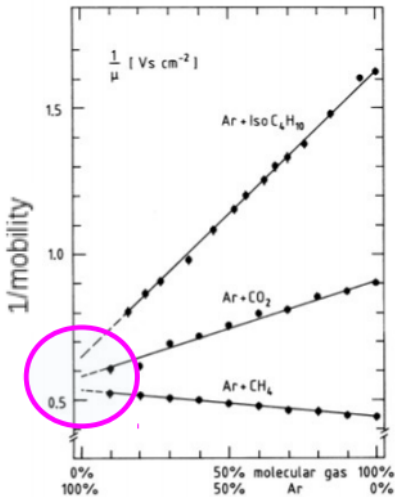
Resistors
in parallel

$$\frac{1}{K_{TOT}} = f_1 \frac{1}{K_{11}} + f_2 \frac{1}{K_{22}}$$

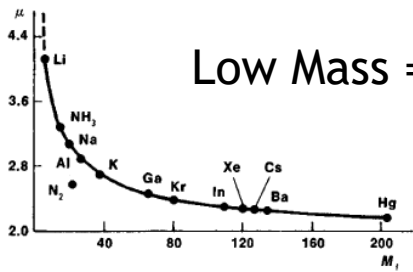
Flat at all
Reasonable
Drift Fields



Measurement of Blanc's Law



- ▶ ALICE Neon mixture helps (6X better than STAR)
- ▶ In my opinion, reducing ion mobility will likely force us to use a neon-based mixture.



Low Mass = High Mobility

Gas	$K \left(\frac{\text{cm}^2}{\text{Volt} \cdot \text{sec}} \right)$	$v_D \left(E = 130 \frac{\text{V}}{\text{cm}} \right)$	$v_D \left(E = 400 \frac{\text{V}}{\text{cm}} \right)$
Ar	1.51	196	604
Ar-CH ₄ 90:10	1.56	203(STAR)	624
Ar-CO ₂ 90:10	1.45	189	582
Ne	4.2	546	1680
Ne-CH ₄ 90:10	3.87	503	1547
Ne-CO ₂ 90:10	3.27	425	1307(ALICE)
He	10.2	1326	4080
He-CH ₄ 90:10	7.55	981	3019
He-CO ₂ 90:10	5.56	722	2222
T2K	1.46	190(ILC)	584

Ion Back Flow

- ▶ Ion Back Flow measurements are receiving attention as never before.
- ▶ Both Yale (EIC/ALICE) and Munich (ALICE) have performed extensive measurements.
- ▶ Universal (natural) trend emerges:
 - ▶ Since IBF from 1st GEM is ~100%, the IBF is controlled by GEM1 gain.
 - ▶ Fluctuations in 1st stage gain define limiting energy resolution.
- ▶ Gain stage has TUNABLE performance
 - ▶ Ion+Ion ... low IBF
 - ▶ e+Ion ... good E-resolution for PID.

ALICE does not have this luxury, but we do!

Quad-GEM Solution for ALICE

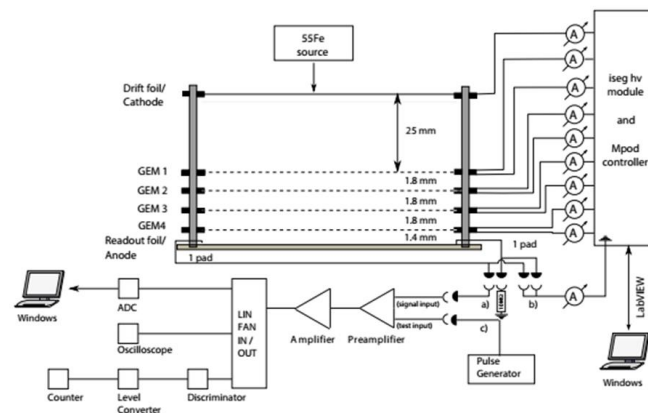
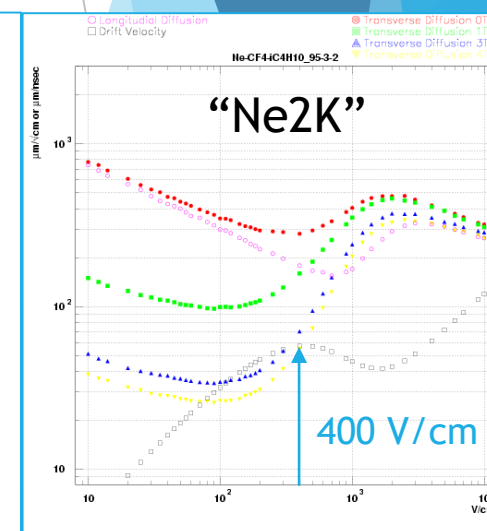
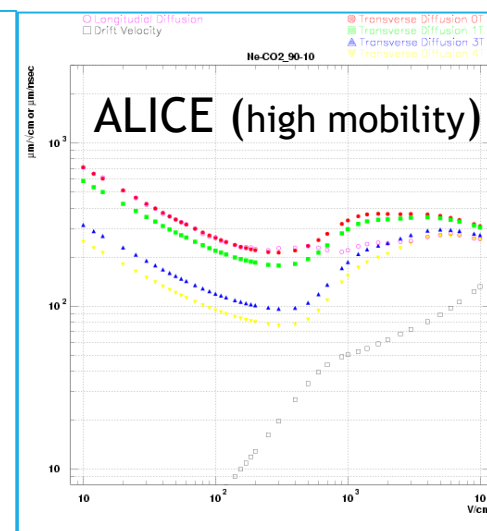
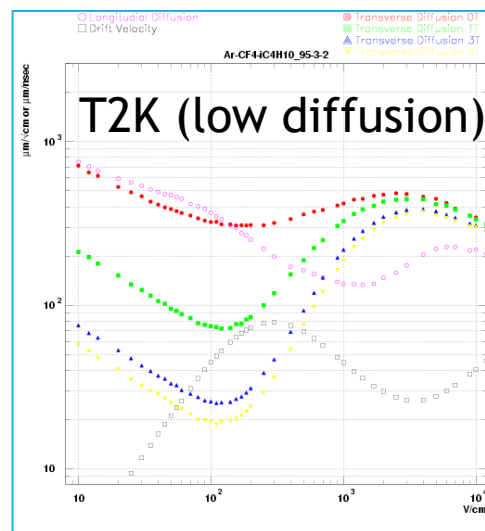
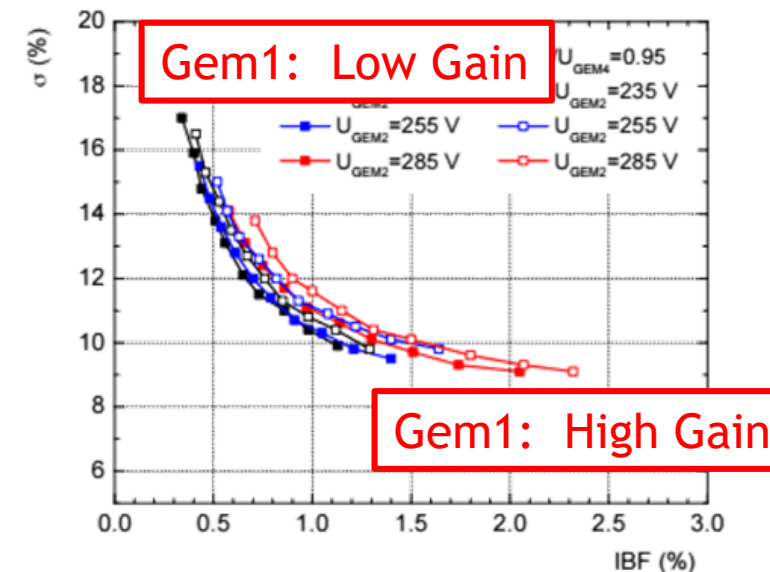
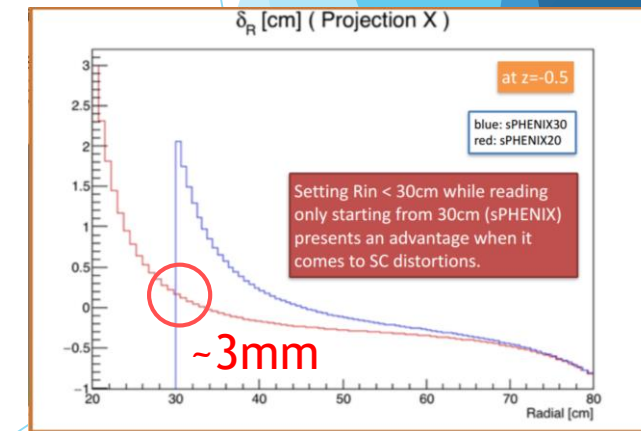
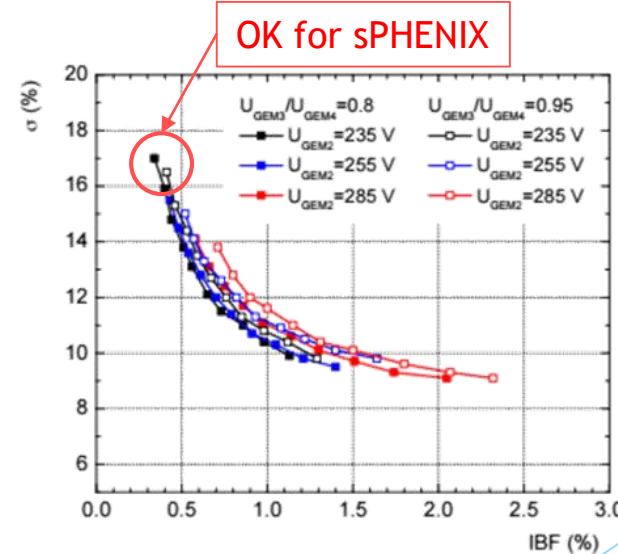


Figure 5.1: Sketch of the Munich quadruple GEM setup.



Aces in the Hole

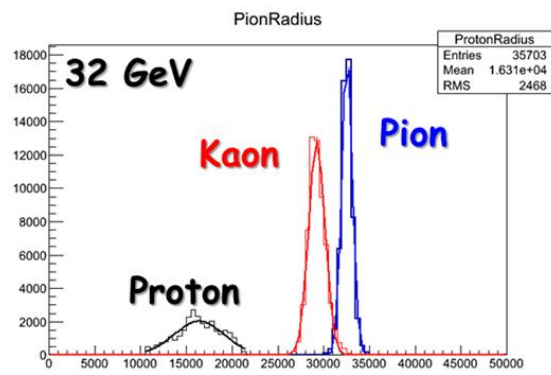
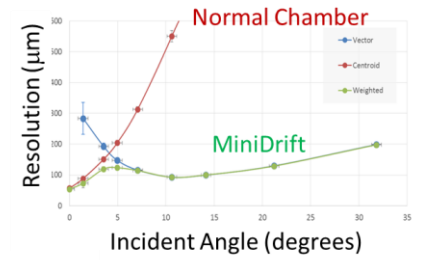
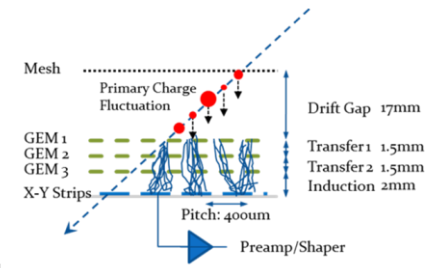
- ▶ The Baseline sPHENIX program does NOT require dE/dx from the tracker.
- ▶ We can select an operating point that favors low IBF for heavy ion collisions and then regain dE/dx for EIC simply by changing the voltages.
- ▶ We can maybe choose a lower ionization gas (already must go to Ne...He is also possible).
- ▶ We can operate using gasses that are more forgiving (Ne CO₂ is NOT on the velocity plateau) of imperfections in temperature/field.
- ▶ We can “hedge” the IBF issue by moving the internal window inward (remember, deflection due to relative space charge)---BIG EFFECT.
- ▶ We can possibly develop Gain==1 IBF shield using tricks learned from EIC RICH prototype and ILC TPC.
- ▶ We can even install a Wieman grid.



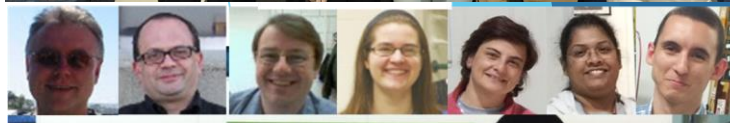
Note: Because of the 1.5 T field, the $rd\phi$ distortion in sPHENIX is comparable to dr .

Bold Schedule to Advance TPC Project

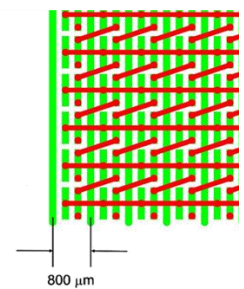
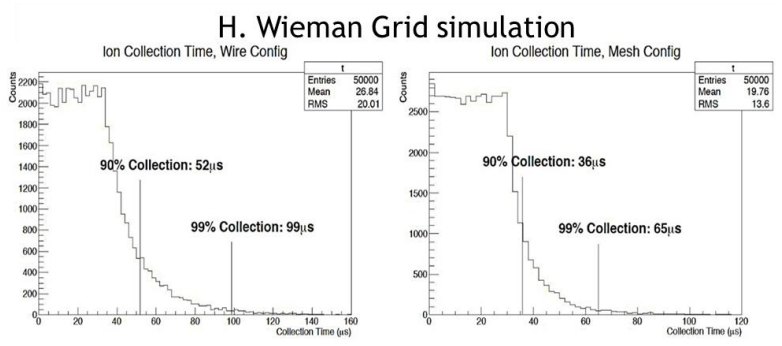
- ▶ All sPHENIX detector systems require a multi-stage R&D program:
 - ▶ v1 prototype
 - ▶ v2 prototype
 - ▶ Pre-production module
- ▶ Much R&D on GEM-based detectors has been done by “us” via the eRD6 program.
- ▶ Our R&D should address the “scaling issue” of large MPGD already at the v1 level.
- ▶ The v1 phase has received funds from SBU and LDRD.



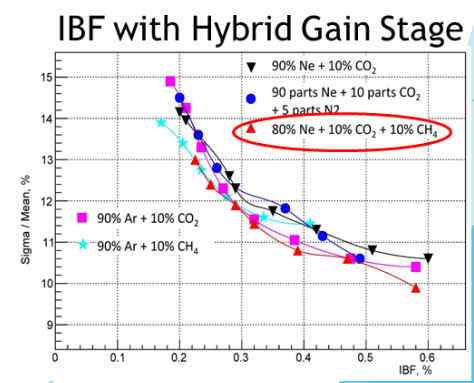
TPC/Cherenkov Test Beam April 2016



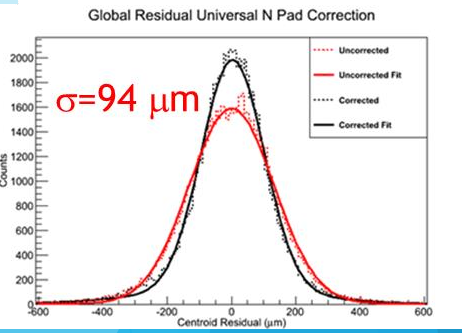
Minidrift TPC Test Beam October 2013



- 3-coordinate:
- $\sigma_x = 66 \mu\text{m}$
 - $\sigma_y = 85 \mu\text{m}$
 - $\sigma_u = 73 \mu\text{m}$

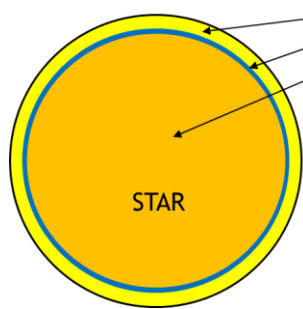


Small TPC w/ Chevrons

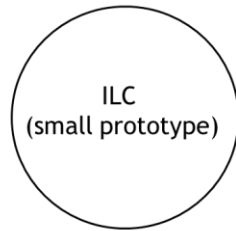


TPC Design Inspiration

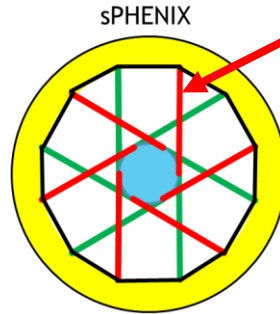
- ▶ Mainly from STAR/ILC (ALICE 3-layer design uses too much radial space).
- ▶ Manufacture technique hybrid between STAR and ILC.



Machinable Foam
Rope
Wood

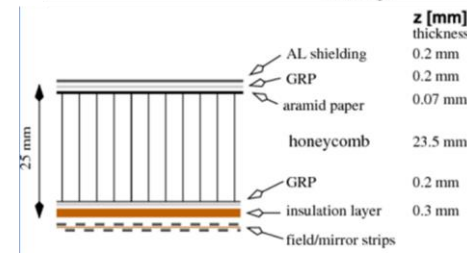
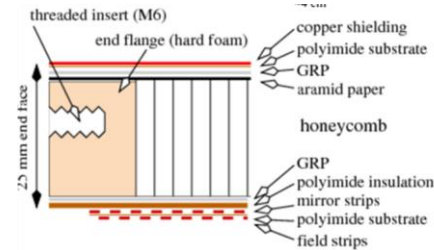


ILC
(small prototype)



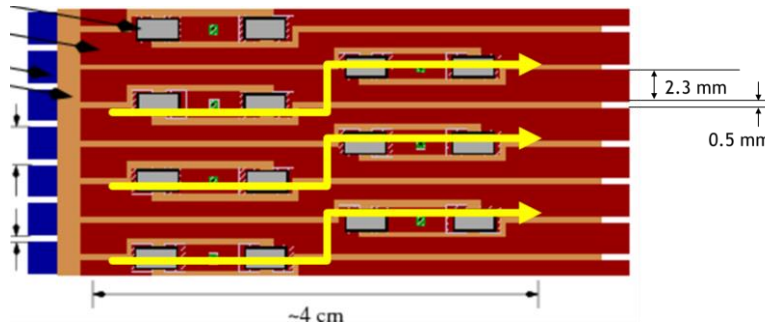
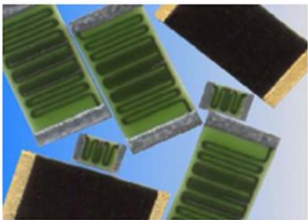
sPHENIX

Disassemble spokes
to release field cage.



High Voltage Testing

Stackpole Electronics, Inc.
Resistive Product Solutions



NOTE: Thicknesses not to scale



Cu-clad FR4 (few mils)

1/2" Hexcell

HVPF Field Cage Board

Field Cage Mandrel Under Construction



3/22/2016

HVC Series

High Voltage Thick Film Chip Resistor

- Features:
- Absolute voltage ratings up to 40,000 volts
 - Ohmic values to 50G
 - Available with wire bondable terminations
 - Tight tolerances to 0.1%
 - Utilizes fine film resistor deposition technology
 - Superior pulse handling capabilities
 - Low TCR to 25 ppm/°C
 - Low VCR to 1 ppm/volt
 - Very low noise
 - Ultra high stability
 - Custom sizes available
 - Higher or lower resistance values may be available (contact factory)
 - Standard HVC parts are unmarked
 - RoHS compliant

Barrel of field cage

- ▶ Turn machinable foam down to desired radius.
- ▶ Pre-drilled holes allow section-by-section of the mandrel to become vacuum head to hold long “striped” kapton.
- ▶ Harmonic drive motors with 1 micron absolute position sensors position digital microscope for accurate electrode placement.
- ▶ Magnetic particle brake rollers deliver fresh kapton under uniform tension to wind up the insulating layer.
- ▶ Asymmetric honeycomb forms natural cylinder.
- ▶ Lathe action allows end pieces to be “faced off perpendicular”
- ▶ Spoke disassembly disengages field cage from mandrel.



Contribution

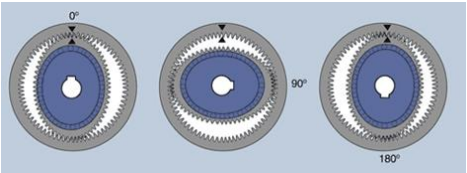
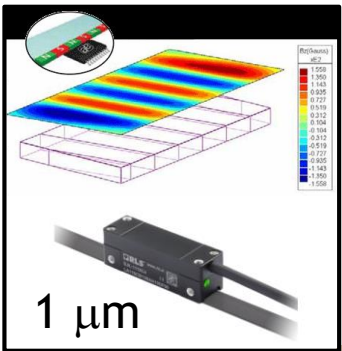


Commitment

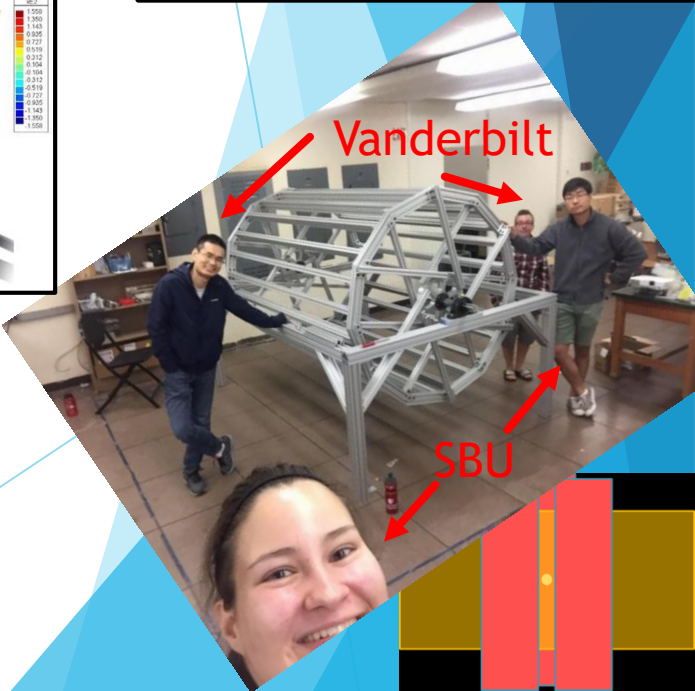
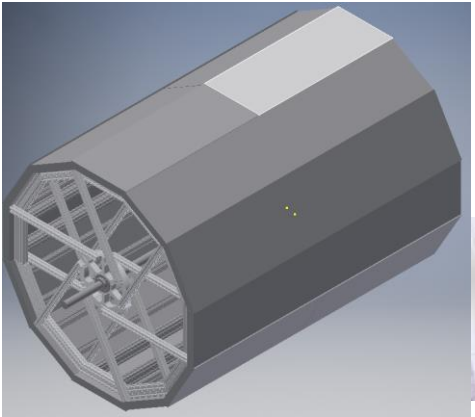
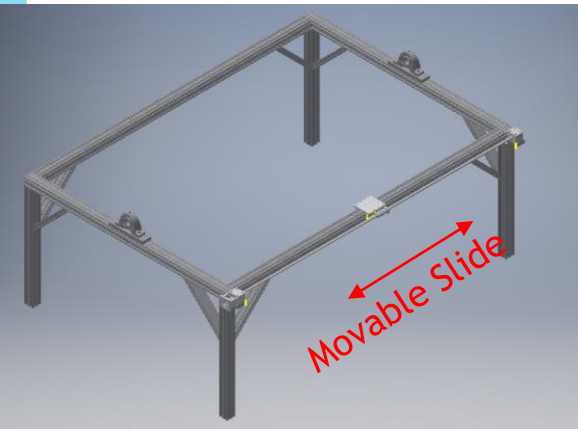
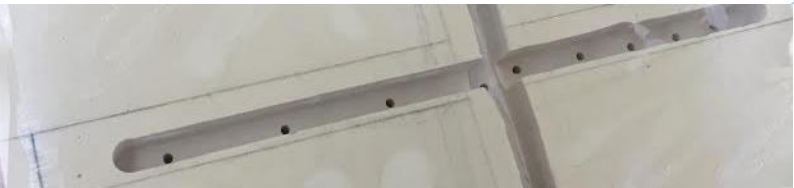


Item	Vendor	Total	Status
HVPF Boards	Sierra Express Circuits	\$12,564.55	DELIVERED
8020 parts	McMaster-Carr	\$7,959.44	DELIVERED
Clean Hood Motor Repair	Grainger	\$554.75	DELIVERED
Tooling for Mandrel Table	McMaster-Carr	\$774.82	DELIVERED
Optical readout for DVM (IBF)	Mouser	\$79.99	DELIVERED
TOTAL		\$21,933.55	

SBU-funds to kick off v1



Backside routed for vacuum head



High Voltage Pulse Withstanding Resistors

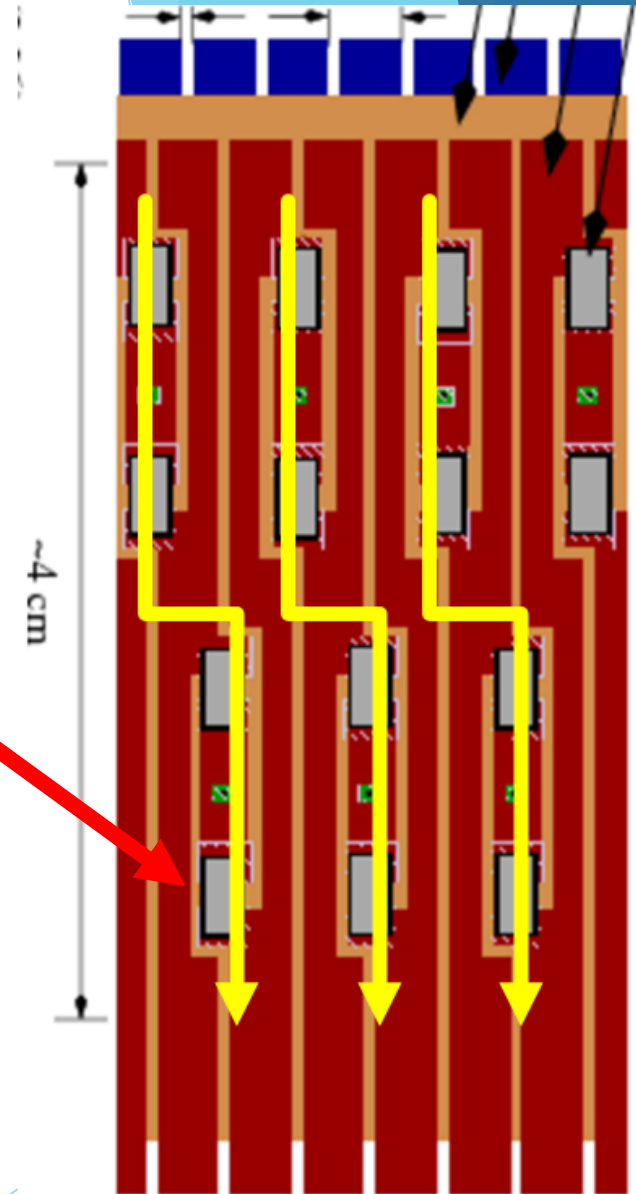
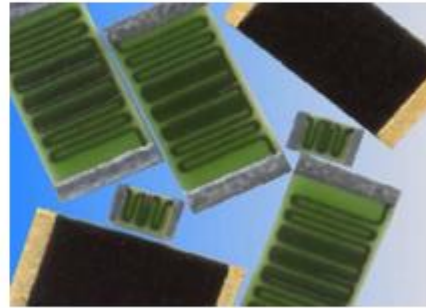
HVC Series

High Voltage Thick Film Chip Resistor

Stackpole Electronics, Inc.

Resistive Product Solutions

- Features:
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 - Available with wire bondable terminations
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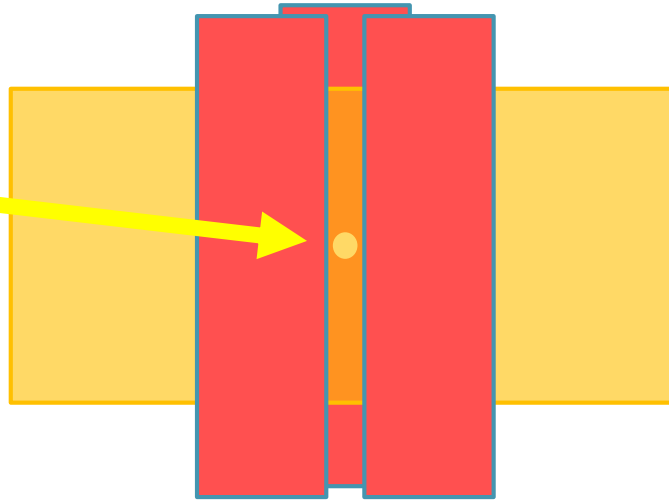


ILC Resistor Chain

- ▶ WOW! Small package surface mount resistors that:
 - ▶ Withstand big HV pulses/
 - ▶ Are available with small temp coefficient (25 ppm/C).
 - ▶ Are available in 0.1% precision!

Field Cage Survey Technique

We can “view” a reference mark located on the INTERNAL field stripe to survey field cage



- ▶ Cool microscope trick:
 - ▶ Etch “alignment mark” on the inside stripe.
 - ▶ Look THROUGH kapton at the alignment mark to set stripes.
 - ▶ NO affect of front-back registration errors from manufacturer

Progress on tooling (mandrel)

- ▶ Only a single pending order on the tensioning mechanism for kapton delivery remains.
- ▶ Long lead time items to be delivered near beginning of August.
- ▶ Ready to cut foam Real Soon Now!

Item	Vendor	Min Units	Ordered	Price	Total	Status	Basis of Estimate	SubComponent Total
FR4520 tooling Foam	General Plastics	6	7	623.14	\$4,361.98	ORDERED		
2" diameter 9' long shaft	Technico	1	1	335	\$335.00	DELIVERED		
RSF-14B-30-F100-24B	Harmonic Drive	1	1	1330	\$1,330.00	ORDERED		
SHA32A161SG-B12BLV-10S17b-AN	Harmonic Drive	1	1	4674	\$4,674.00	ORDERED		
8020	McMaster-Carr				\$4,277.84	DELIVERED		
Laminate Trimmer	Grainger	1	1	155	\$155.00	DELIVERED		
Position Encoders	Renishaw				\$1,202.00	ORDERED		
Adhesive, lab supplies	McMaster-Carr				\$1,440.43	DELIVERED		
Lead Screw	Lin Tech				\$3,456.00	DELIVERED		
2" flanged Collars for motor/encoder	McMaster-Carr				\$371.66	DELIVERED		
USB microscope	Microscope Store				\$143.00	DELIVERED		
Motor Controllers	Copley Controls				\$1,637.00	DELIVERED		
SM encoder	Automation Direct				\$67.25	DELIVERED		
SM motor	MicroMo				\$253.49	ORDERED		
Wire/connectors	DigiKey				\$352.41	ORDERED		
PS for translation motor (24 V 24 A)	Automation Direct				\$415.00	ORDERED		
PS for shaft motor (48 V 24 A)	Acopian				\$1,170.00	ORDERED		
Motor Controller Access. Kits	Copley Controls				\$276.00	ORDERED		
Web Tension Applicator Toolset	Sterling Instruments?				\$4,000.00	Pending	Web Search	\$29,918.06



NOTE: Table is just M&S

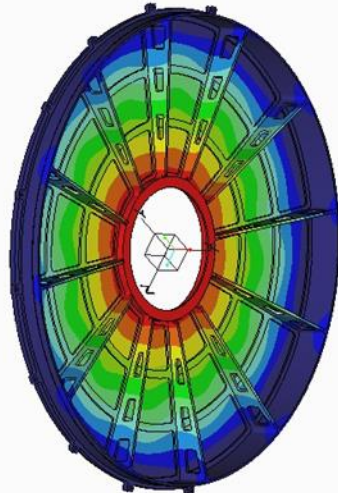
Shell materials becoming well defined.

Outer Barrel

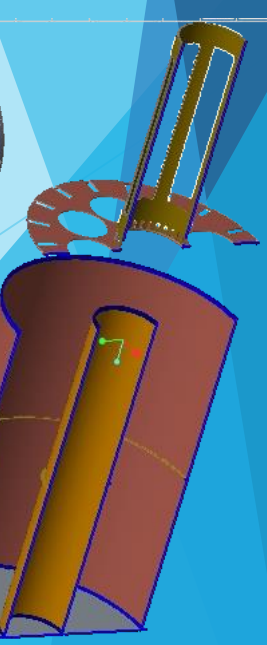
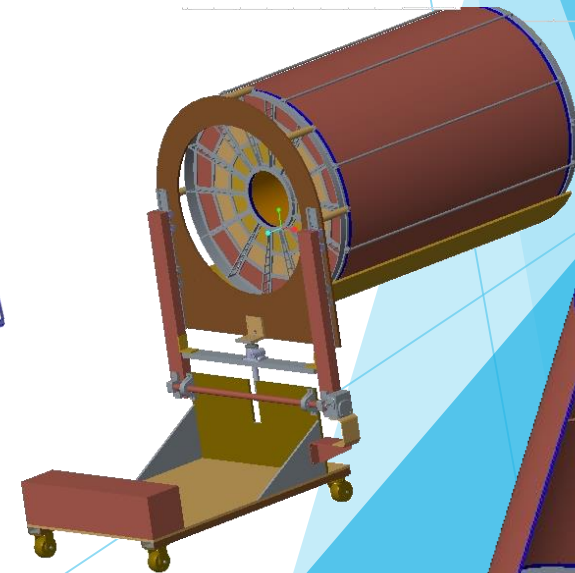
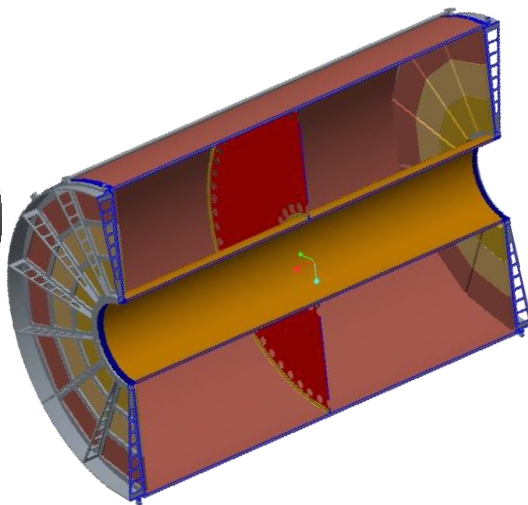
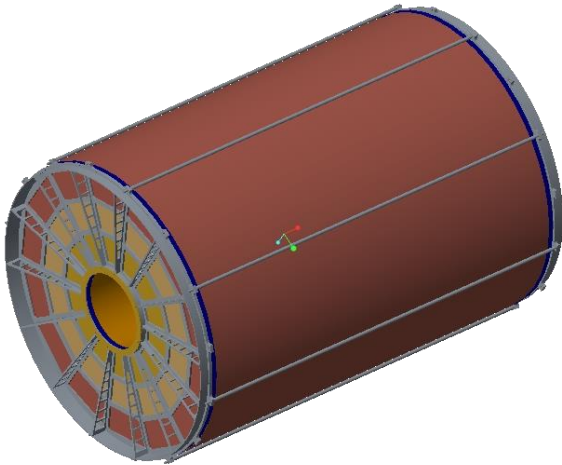
Inner Barrel

Other

Honeycomb	Plascorp	4	6	270.18	\$1,621.08	ORDERED		
Striped circuit cards	All-flex	5	8	2925	\$23,400.00	Pending	Manufacturer Quote	
3 mil kapton 44" x 108 LF	Dunmore	2	3	7260	\$21,780.00	Pending	Manufacturer Quote	
3 mil kapton 22" x 108 LF	Dunmore	4	5	4070	\$20,350.00	Pending	Manufacturer Quote	
FR4 outer sheets 4' x 4'	ePlastics	8	10	114.58	\$1,145.80	Pending	Manufacturer Quote	
HVPW resistors	DigiKey	800	1000	1.17	\$1,170.00	Pending	Manufacturer Quote	
High Voltage Cable	Dielectric Sciences				\$600.00	Pending	Web Search	\$70,066.88
Striped circuit cards	All-flex	5	8	1500	\$12,000.00	Pending	Manufacturer Quote	
3 mil kapton 44" x 108 LF	Dunmore	1	1	7260	\$7,260.00	Pending	Manufacturer Quote	
3 mil kapton 44" x 108 LF	Dunmore	1	2	4070	\$8,140.00	Pending	Manufacturer Quote	
FR4 Sheets 4' x 4'	ePlastics	2	2	114.58	\$229.16	Pending	Manufacturer Quote	
HVPW Resistors	DigiKey	800	1000	1.17	\$1,170.00	Pending	Manufacturer Quote	\$28,799.16
Central Membrane					\$8,000.00		Experience	\$8,000.00
End Caps					\$20,000.00		Experience	\$20,000.00



- ▶ Space frame endcap ala ILC
- ▶ 3 radial segments to improve reliability



John Brodowski (BNL) -- TPC Engineer

BACKUPS

Definitions of L5 items in MS Project file:

- ▶ TPC Prototype v1 (not in file...LDRD, BNL, & SBU funds)
 - ▶ Full size and dimension field cage. Intended for use in sPHENIX.
 - ▶ 1 or more modules (take two...they're small) instrumented:
 - ▶ Temporary connector pattern; No cooling; "Test Beam" electronics.
- ▶ TPC Prototype v2
 - ▶ Reuse field cage, but assume funds for minor reworking.
 - ▶ 1 or more modules reflecting lessons-learned from v1:
 - ▶ Final connector PATTERN; No cooling; "Test Beam" electronics...adapted to connector pattern.
- ▶ TPC Pre-production prototype
 - ▶ Reuse field cage, but assume funds for minor rework.
 - ▶ 1 or more modules reflecting candidate for electronics card
- ▶ Production:
 - ▶ Modules made assembly-line fashion at multiple institutions.
 - ▶ Gas System
 - ▶ Laser System
 - ▶ Cooling System



Discussed in this PowerPoint only

Principle Subject of Project File

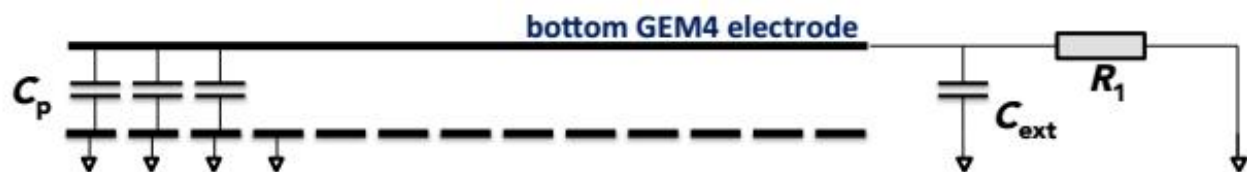
Some News from ALICE review:



H. Appelshäuser, Goethe-Universität Frankfurt

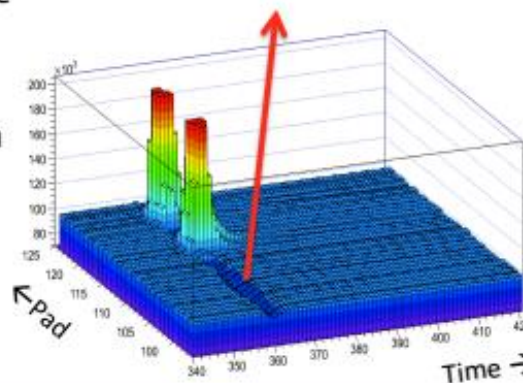
Common Mode Effect

Effective baseline shift and noise due to capacitive coupling of amplification structure (wire, GEM) to pads



Measurement in MWPC:
Effect visible as negative
pulses on many pads

Common mode signal



- possible effect on zero suppression and resolution
- TDR: online treatment using **DSP functionality** in SAMPA
- **detailed microscopic physics performance study of DSP**

- ▶ Common Mode removal is what the on-board DSP for the SAMPA chip is designed to do.
- ▶ The technique:
 - ▶ Find a large number of “empty channels”.
 - ▶ See if they all dip below zero together.
 - ▶ Correct everyone up by the amount of the dip.
- ▶ The weakness:
 - ▶ You **MUST** find enough channels (give the occupancy) to make the determination accurately.

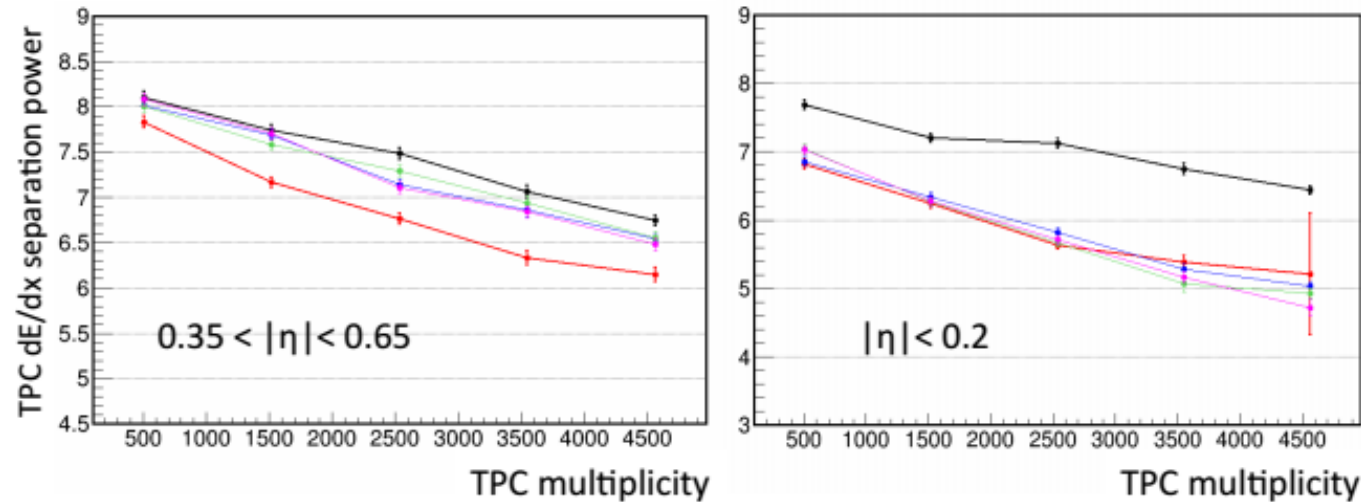
But SAMPA has only 32 channels!!



ALICE-USA
BTU Project

H. Appelshäuser, Goethe-Universität Frankfurt

dE/dx Performance of DSP

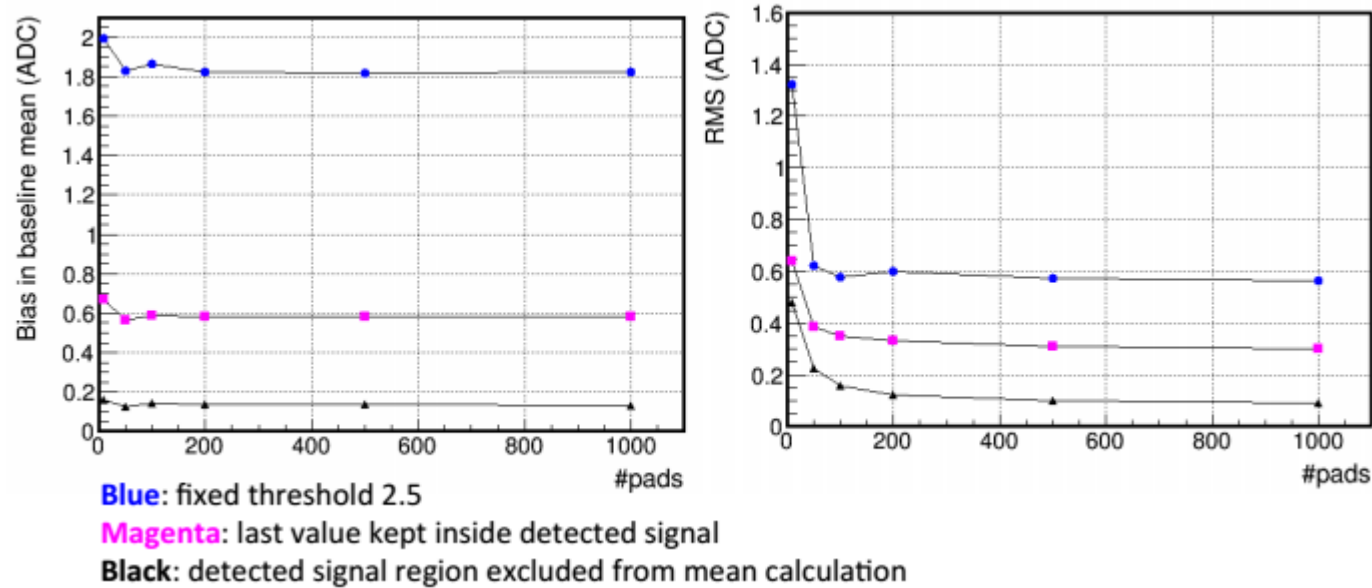


- without common mode
- with common mode
- blue, magenta, green: different slope settings in BC3 filters
- deterioration up to 20% in central events
- eta dependent
- further „offline“ calibration possible (as in Run1)

► Scheisse!

- At the highest rate in ALICE, the limitation of “seeing” only 32 channels degrades energy resolution.
- Intolerable for ALICE.
- sPHENIX does not desire high resolution dE/dx...
- EIC era will return to low occupancy and 32 channels will likely be enough.

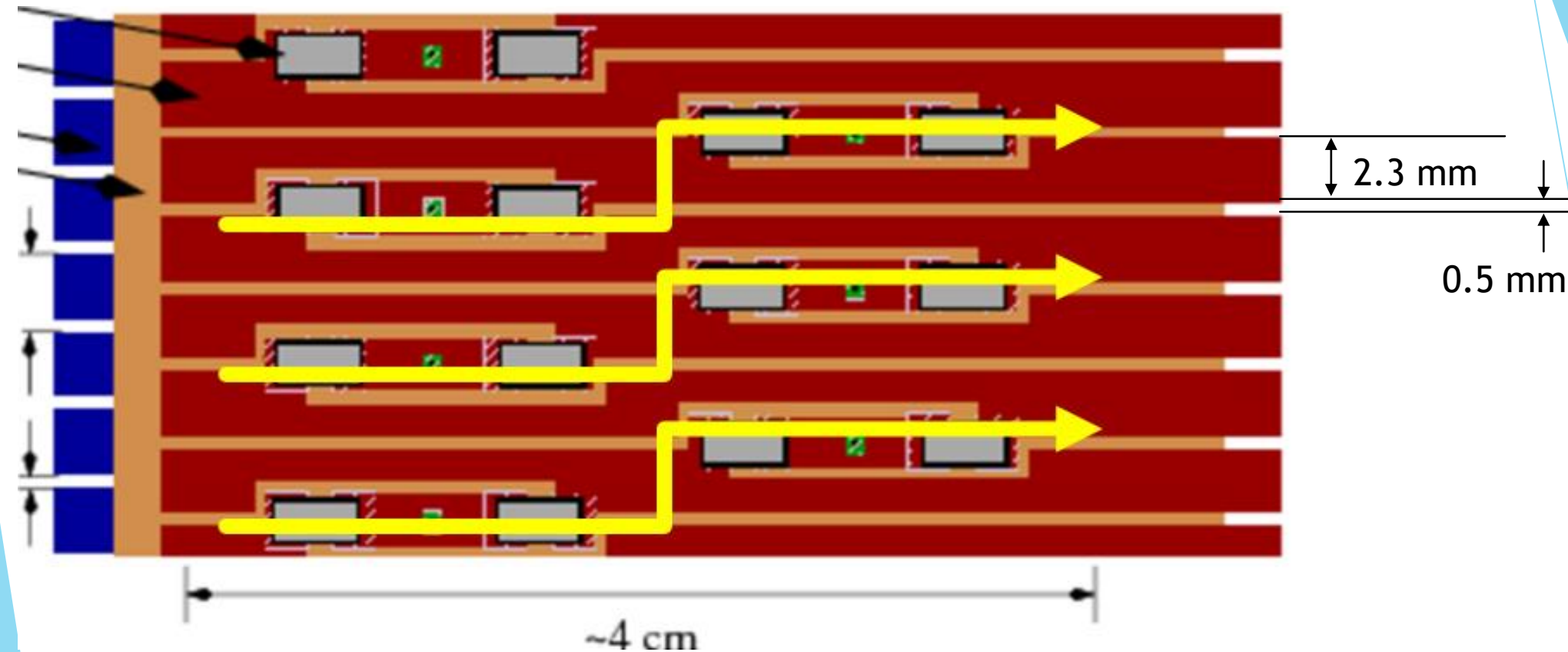
Their remediation plan



- ▶ Monte Carlo indicates no improvement in performance beyond 100-200 pads.
- ▶ Options:
 - ▶ Add FPGA onto FEE (one card sees 5 SAMPA = 160 channels).
 - ▶ Send raw data using EXTRA fibers and process on the CRU.
 - ▶ Send raw data, but digitize @ 5 MHz using existing card design.

Muon systems WILL use the SAMPA DSP since their occupancy is lower. We would almost certainly use the DSP at full speed and it will meet our needs.

Stripes design nearly 100% complete!



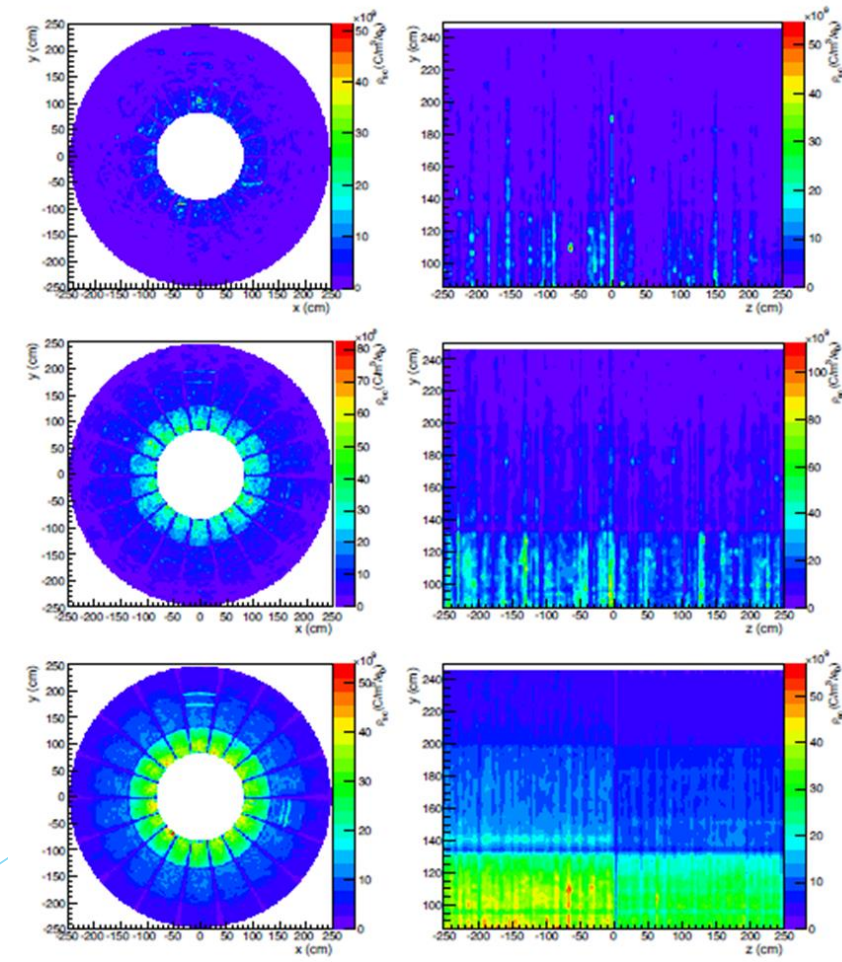
- ▶ New resistor technology reduces resistor size dramatically.
- ▶ Kapton circuit company will apply these resistors!
- ▶ Very fine pattern means much better field quality.

Outline

- ▶ Some non-Engineering Updates that Impact Engineering.
 - ▶ Space Charge immediate actions:
 - ▶ Two known methods minimize space charge distortions A LOT!
 - ▶ Influence on inner field cage location.
 - ▶ Space Charge possible actions:
 - ▶ More speculative concepts that appear viable can also influence design.
 - ▶ Addition of a “field termination grid” might reduce Ion Back Flow but it WILL CERTAINLY RELAX MECHANICAL TOLERANCE CONSTRAINTS (so I kinda like it...)
- ▶ Some direct Engineering updates:
 - ▶ $\eta = \pm 1.1$ (not 1.0) ... makes the TPC longer.
 - ▶ Radius change proposal dropped...retain 78 cm.
 - ▶ Future upgrades needs the space.
 - ▶ EMCAL may need the space.
 - ▶ Cross-check chamber (calibrates space charge distortion) needs the space.
 - ▶ Clarified exact parts for table motion purchase (Harmony Drive Motors!)

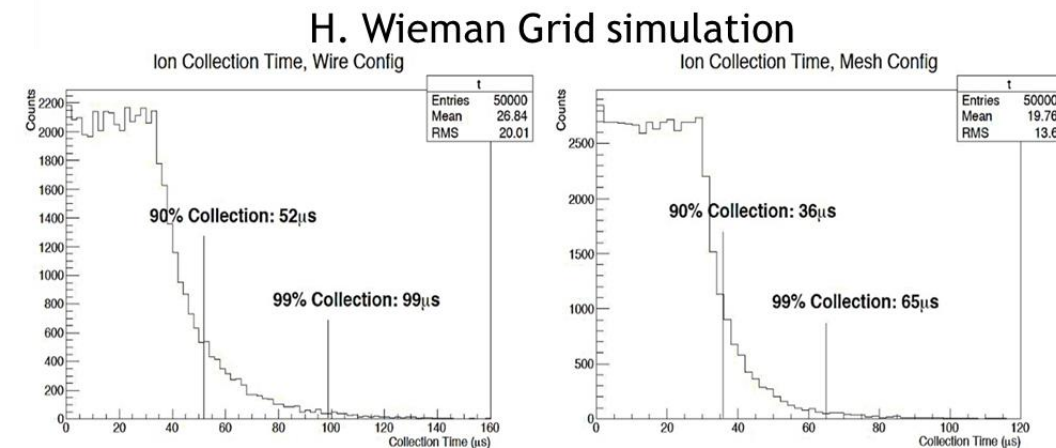
Space Charge: The Boogeyman

- ▶ Distortions can be ENORMOUS:
 - ▶ STAR: 10 cm peak distortion corrected to 400 microns (0.4 %)
 - ▶ Corrects for primary charge only (gated TPC ~no Ion Backflow from gain stage).
 - ▶ Uses analytical phi-symmetric correction driven by current luminosity.
 - ▶ ALICE: 20 cm distortion corrected to 200 microns. (0.1%)
 - ▶ Ion Back Flow = 20X larger than primary charge.
 - ▶ Uses continuous readout to determine INSTANTANEOUS space charge (every 5 msec)
 - ▶ 3D correction since IBF determined by GAIN (gaps, dips, horror).
- ▶ Our advantages:
 - ▶ Only the physics of the effect is given.
 - ▶ Smart design can minimize the impact



Input to IBF calculation IBF (aka ε)

- ▶ Use Ne-based mixture (currently Ne-CO₂ 90:10).
 - ▶ Run at low end of IBF PURPOSELY degrading dE/dx in favor of low IBF (0.3% vs 1.0%)
 - ▶ Move inner field cage to avoid peak.
- Applied Now...
- ▶ Known aces in the hole:
 - ▶ We can maybe choose a lower ionization gas (already must go to Ne...He is also possible).
 - ▶ We can operate using gasses that are more forgiving (Ne CO₂ is NOT on the velocity plateau) of imperfections in temperature/field.
 - ▶ We can add a Weiman mesh:
 - ▶ 10-100X reduction in IBF.
 - ▶ Introduces “static” 10-20% permanent dead time.
 - ▶ Speculative Ace in the Hole:
 - ▶ We can possibly develop Gain==1 IBF shield using tricks learned from EIC RICH prototype and ILC TPC.
 - ▶ **Maybe even a simple mesh will do it...**



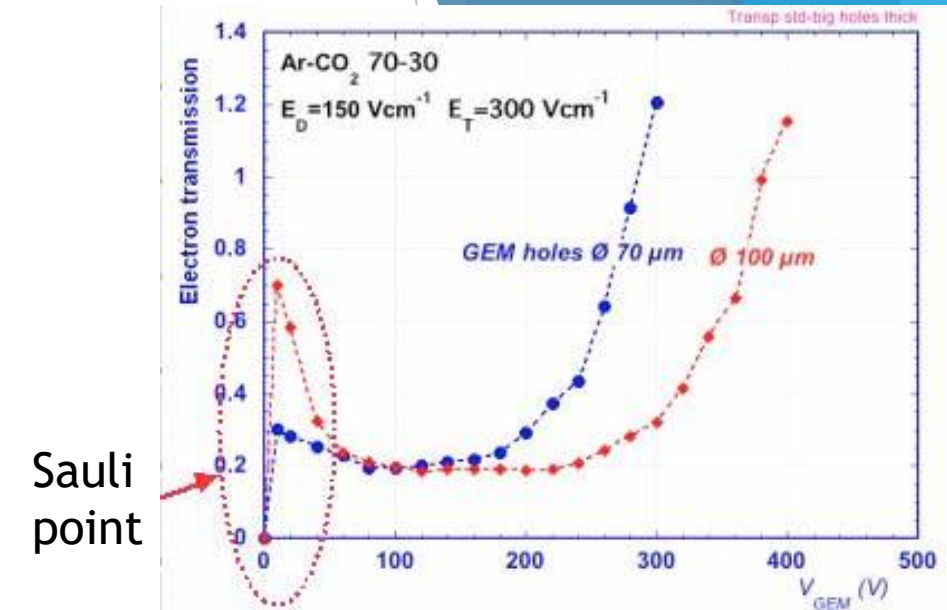
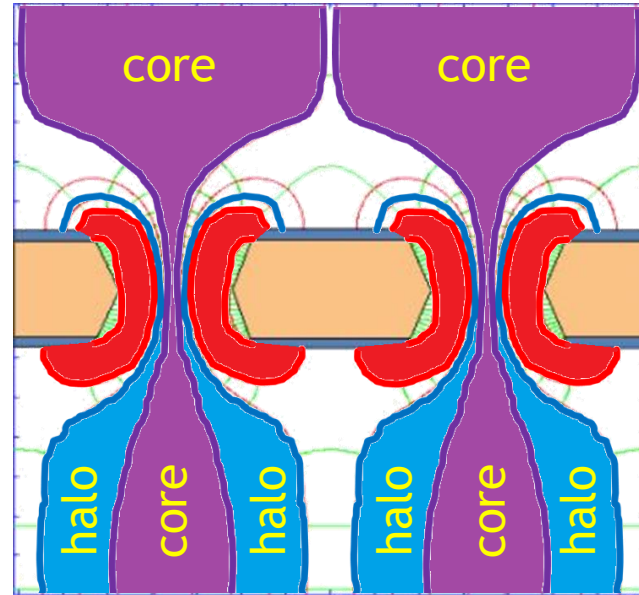
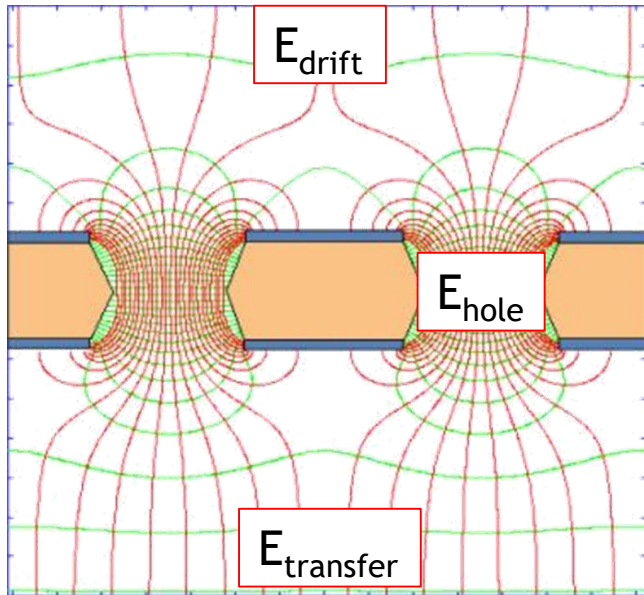
sPHENIX TPC Discussion

chaired by Thomas Hemmick (Stony Brook University)

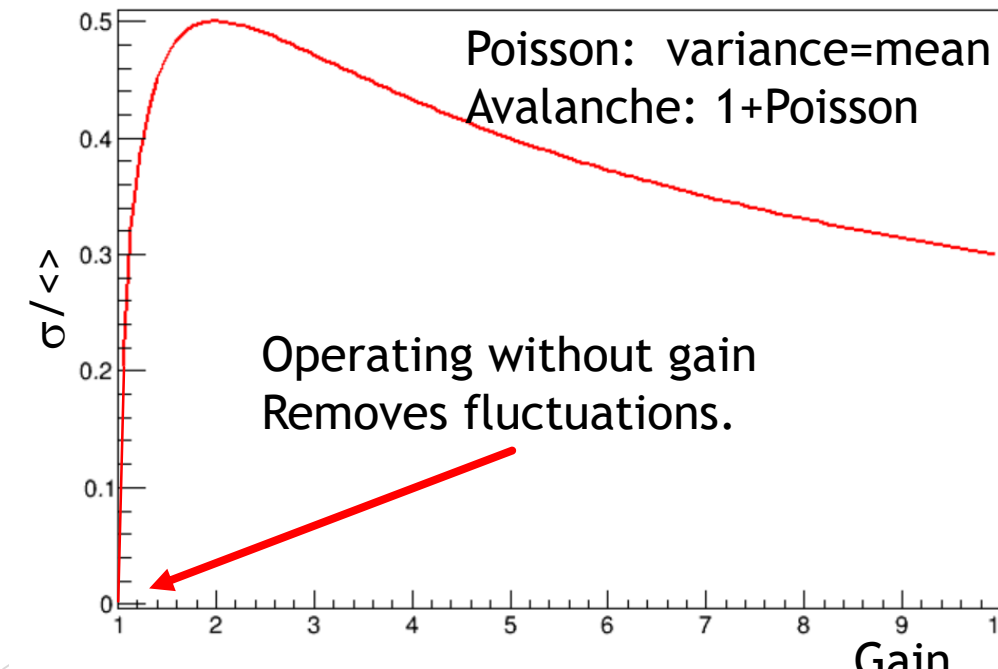
Wednesday, May 11, 2016 from **09:00** to **12:00** (US/Eastern)
at **Universe**

Description Chat about the possibilities for a TPC in sPHENIX with outside experts.

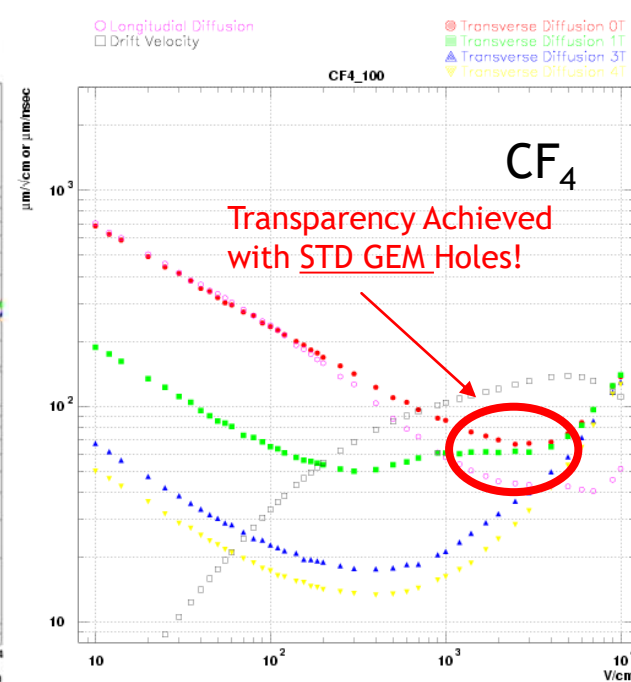
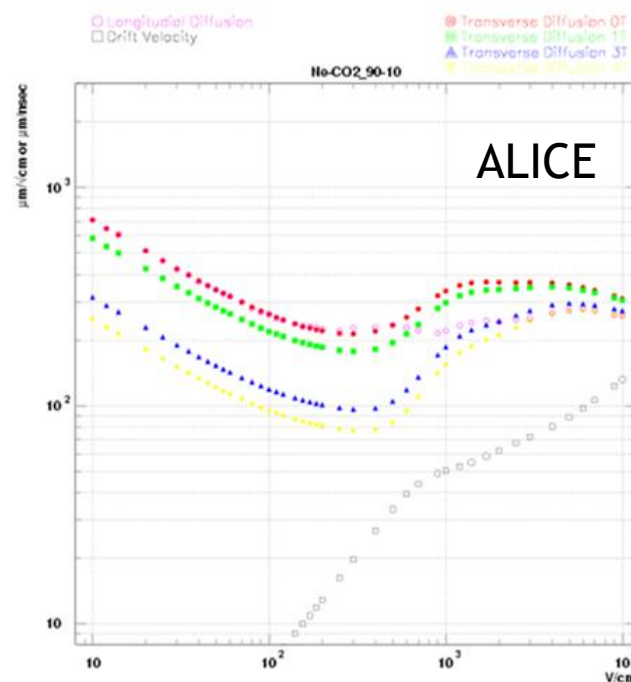
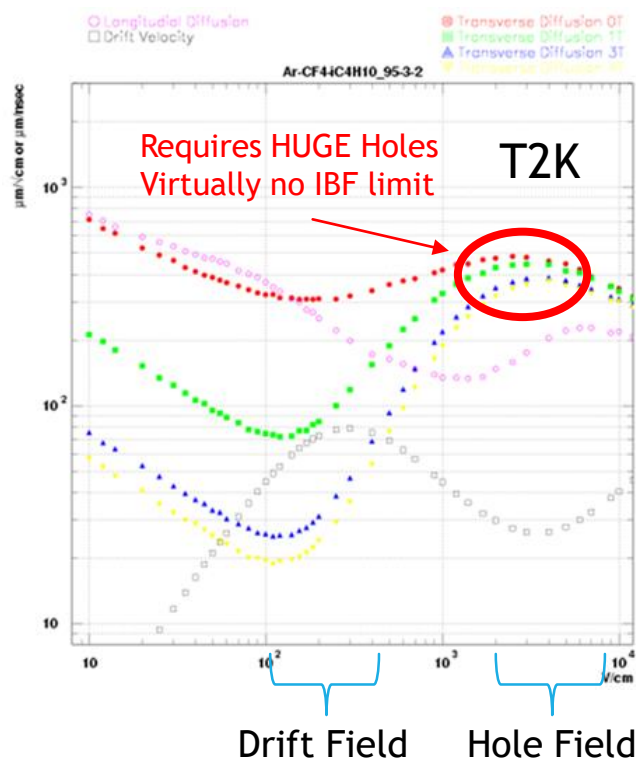
Physics of GEM-influenced Ion BackFlow



- ▶ The limit of no diffusion is not realistic, but quite instructive.
 - ▶ Electrons in the “core” are transported down through
 - ▶ the hole while avalanching.
 - ▶ Ions from halo are lost onto the top GEM while going up.
- ▶ Basic configuration to minimize IBF prefers $E_{\text{transfer}} \gg E_{\text{drift}}$.
- ▶ NOTE:
 - ▶ E-field shapes are SCALE INVARIANT $f\left(\frac{E_d}{E_h}, \frac{E_d}{E_h}\right)$
 - ▶ The scale enters the problem after we impose diffusion in the hole.



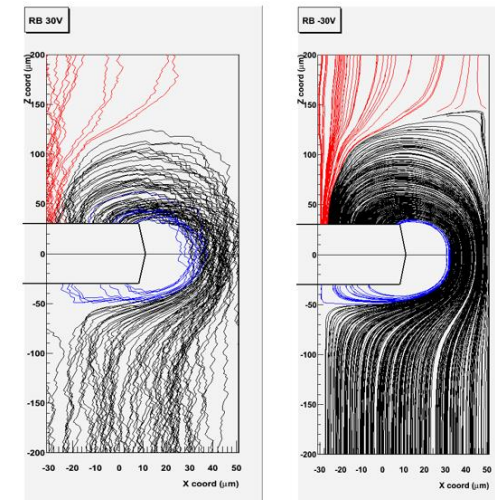
Even lower than 0.3? (expert feedback: promising!!)



Maxwell 3D

w/ diffusion

w/o diffusion



Garfield studies showed that for “ALEPH conditions”, i.e. P10 and B=1.2T, electrons pass the grid at 70% efficiency, while it is 0% for ions. Note that at the nominal ALICE operational point with sigma=12%, the effective electron transparency is only 50%. This would certainly be a very elegant and efficient solution.
-- Harald Appelshaeuser 5-12-2016

Blatnik et al 2015 IEEE Trans Nuc. Sci.
<http://dx.doi.org/10.1109/TNS.2015.2487999>

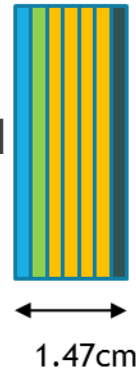
photosensitive GEM at a gain near 1 (using 80% of the nominal ΔV) to minimize this possibility. During our SLAC run we verified that:

- 1) We could indeed operate the detector at gain = 1 in the top layer with no measurable signal loss.

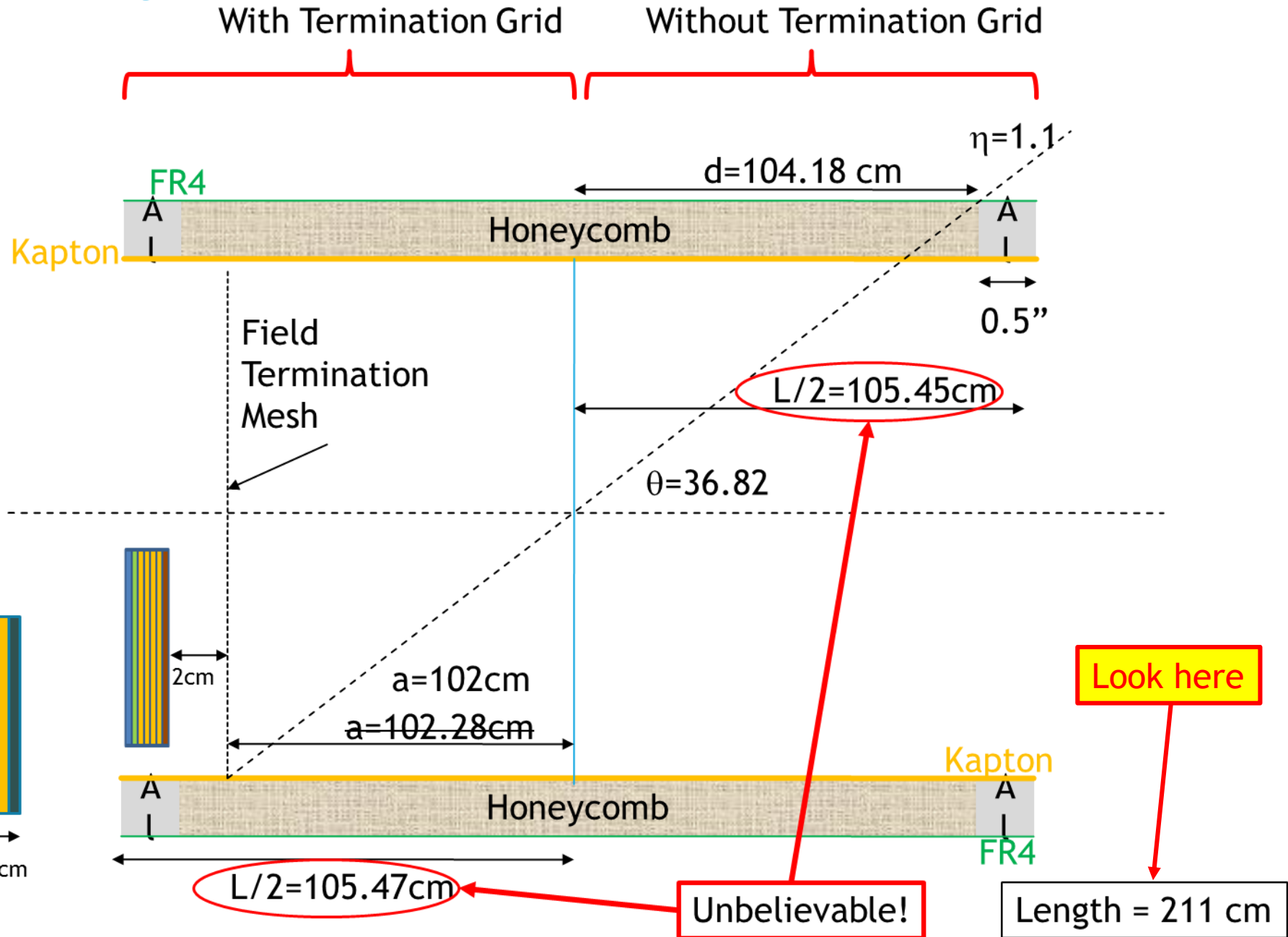
R&D ongoing to determine if viable Gain=1 layer can be achieved.

Getting the Length Right...

- Increases in physical length:
 - Use correct eta.
 - Non-zero readout plane size
 - Clear the Al ring
 - Add a field termination mesh!**
- Field termination mesh will likely reduce IBF.
- Field termination mesh will **CERTAINLY** reduce mechanical constraints on the end plate (but that was easy to meet) and also avalanche stage.
- Fields termination mesh decouples gain voltage and dead channel map from drift field.



Issue: Module swap?



3D model: Inner and Outer Cage

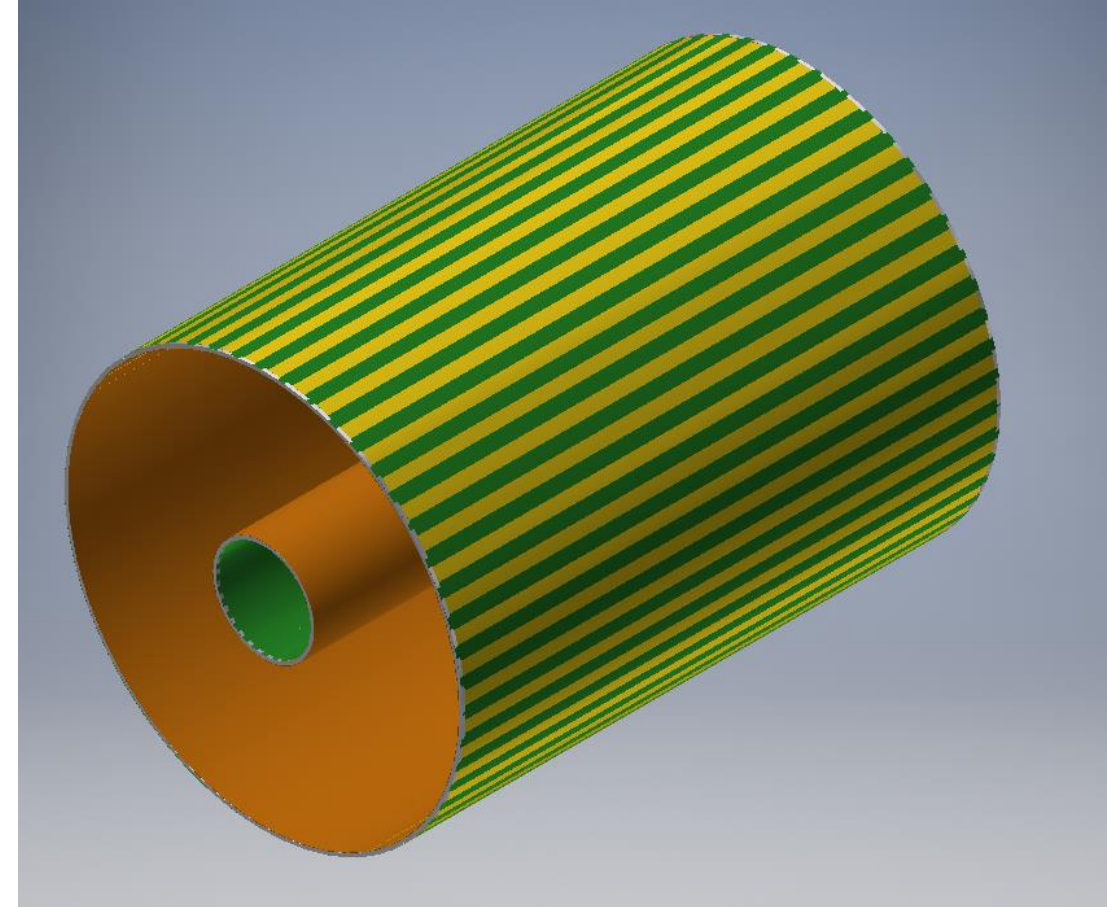
- ▶ How should we transfer files to BNL?
- ▶ Mechanical values for outer TPC field cage (final?):

	formula	cm	in	cm	in
R - outer	#	78		78	30.70866
Skin Thickness	#		0.001	0.00254	0.001
Honeycomb	#		0.5	1.27	0.5
HVPF (kapton)	#	0.15		0.15	0.059055
L (decision)	#	211		211	83.07087

- ▶ Mechanical values for inner field cage (subject to change?)

	formula	cm	in	cm	in
R - gas	#	20		20	7.874016
HVPF (kapton)	#	0.15		0.15	0.059055
Honeycomb	#		0.5	1.27	0.5
Skin Thickness	#		0.001	0.00254	0.001
R-envelope	R(gas) - HVPF - honeycomb - skin	18.57746		18.57746	7.313961

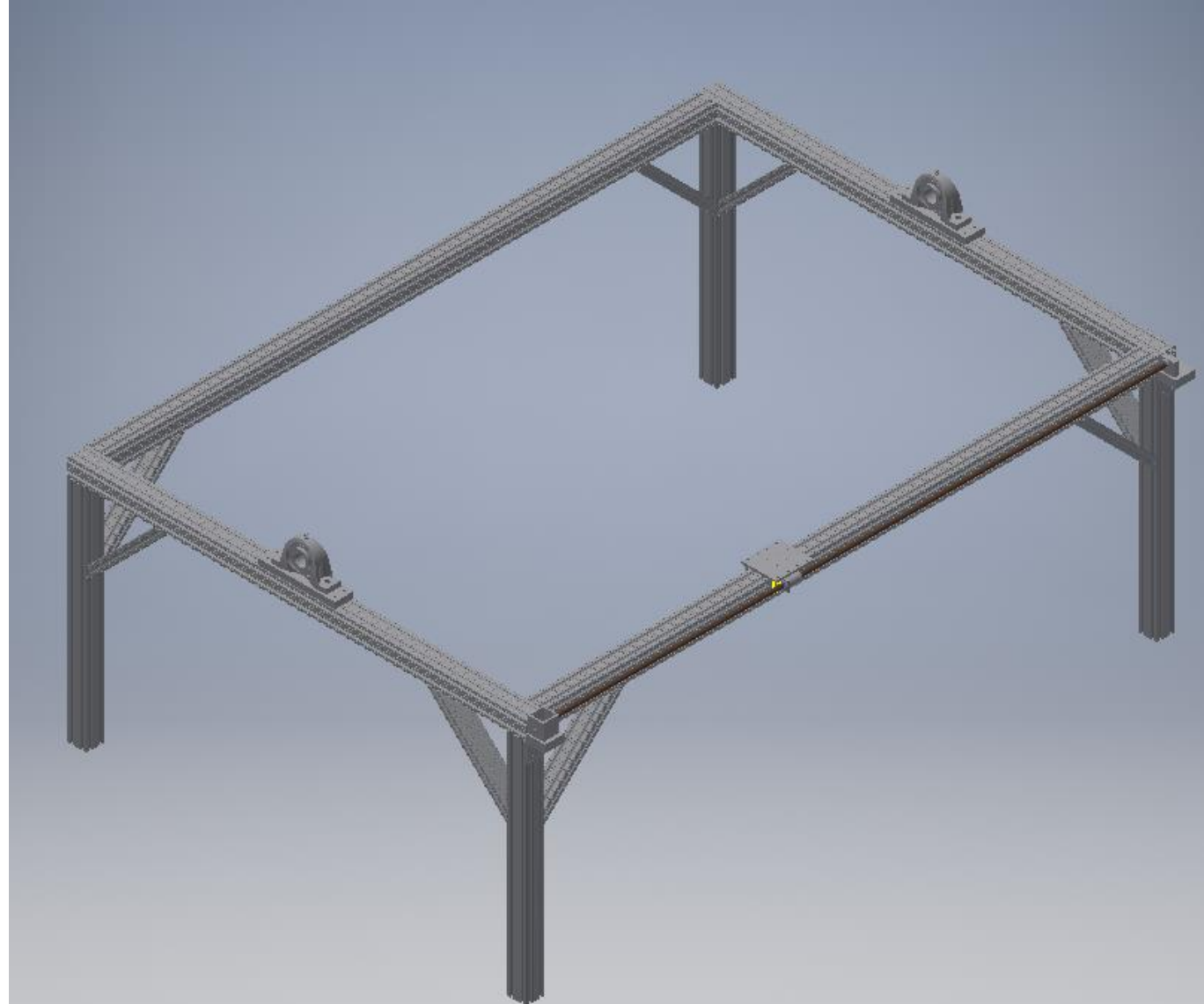
- ▶ Compared to prior drawing:
 - ▶ Length up, HVPF thicker (1.5 mm instead of 1.0 mm), skin added.



All files using Inventor 2016.
We share among students using
the AutoDesk cloud (aka A360)

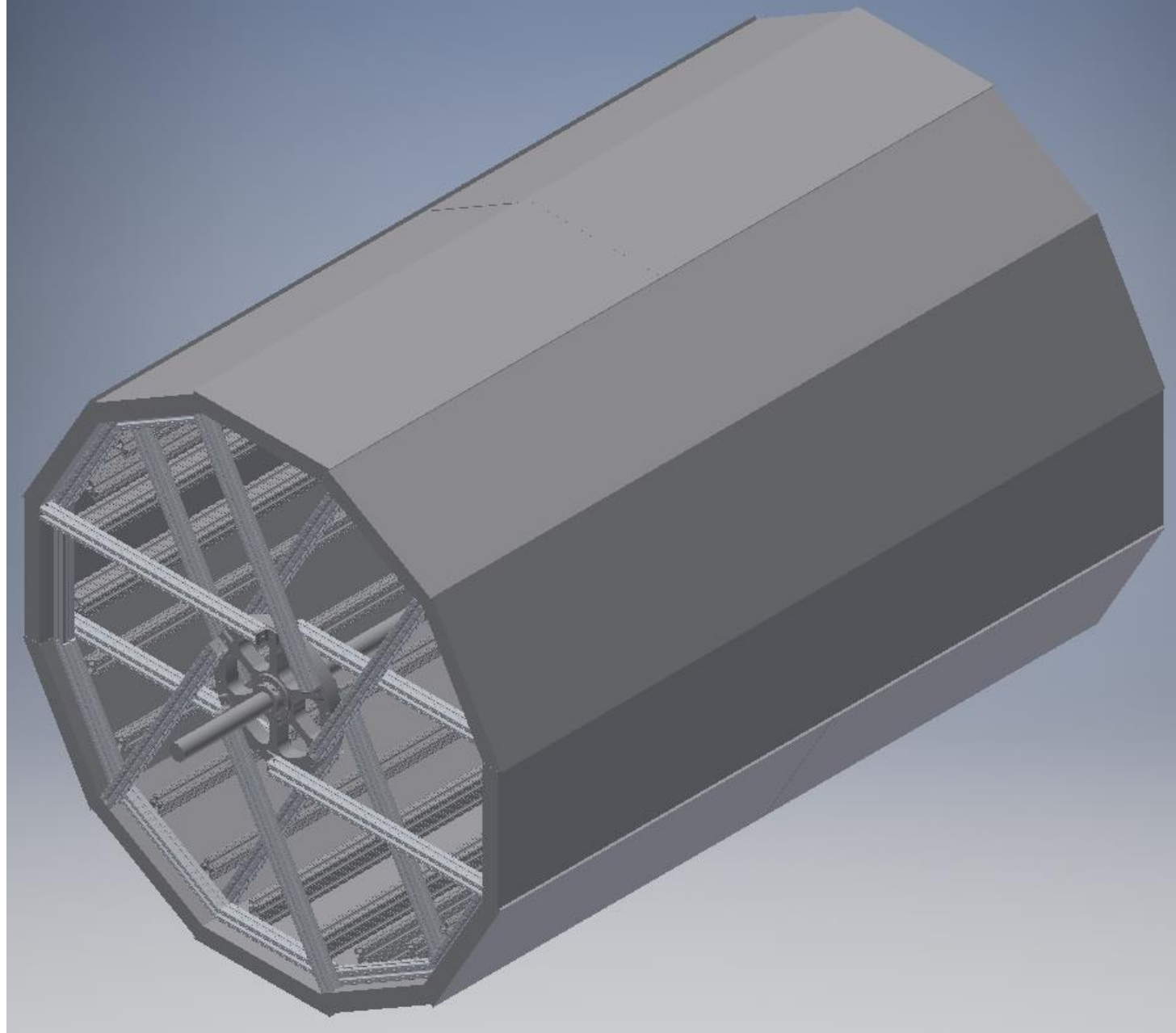
Mandrel gets bigger too:

- ▶ Extended more than just the TPC length:
 - ▶ Allow mandrel surface to be longer than TPC (extra 1.5 “ on each side...just because).
 - ▶ Tool carriage gets 100% clear of the mandrel:
 - ▶ Line of sight to the shaft!
 - ▶ Recalibrate the carriage motion (if needed).
 - ▶ DIRECT measurement of cutting tool radius.
 - ▶ The round up to even feet (95” → 8 feet).
- ▶ Concern:
 - ▶ Bowing of the shaft goes as L^3 .
 - ▶ Load of central worrysome.
 - ▶ New idea: Eliminate center wheel.



New Mandrel

- ▶ Use long (80") 1.5" x 3" 8020 struts running the full length.
- ▶ Should be more than stiff enough to keep the shape.
- ▶ Likely we will make 8020 around the rim of each wheel also double material.
- ▶ Significant news on investigation of parts options!



FR-4520 instead of FR-7120

- ▶ Alternative foam.
- ▶ Roughly the same cost as 7100.
- ▶ Leaves much smoother finish.
- ▶ All chips, very little dust!
- ▶ Modulus only 1% lower than same density 7100 material.
- ▶ Samples on the way from LI distributor.
- ▶ Tan instead of yellow.



Advantages

- Machined anti-static foam boards create shavings that fall to the floor, not dust
- Excellent consistency and uniformity throughout entire mass of material
- Easily finished with nearly any resin or coating system
- No glass-bead fillers to damage cutting tools – material cuts with HSS cutters!
- Long-term durability and dimensional stability
- Always flat and stable – sheets will not warp, bow or twist
- Individual densities color-coded for easy identification

Encoders for table motion



LM13 magnetic ring encoder system

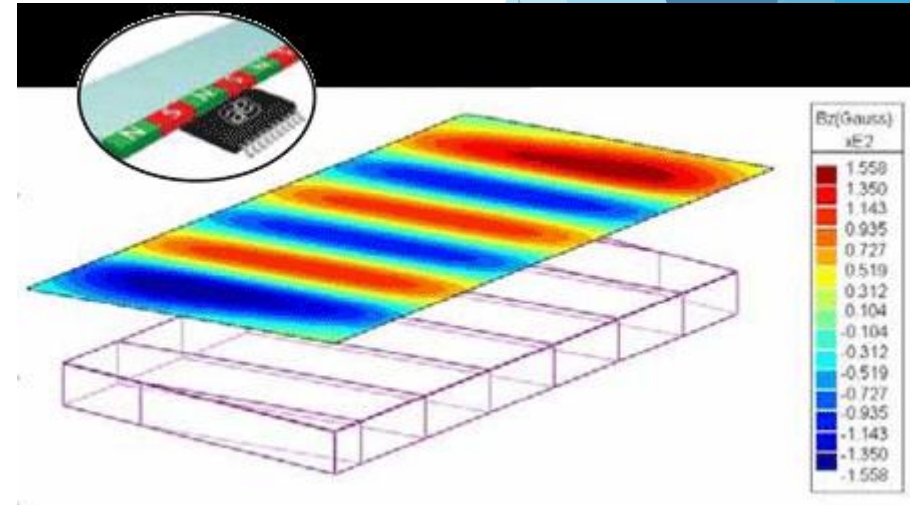
- Resolutions from 1,280 to 327,680 counts per revolution
- High speed operation to 20,000 revolutions per minute
- Excellent dirt immunity



- ▶ Must use magnetic encoders since dust (now chips) interfere with the optical encoders.
- ▶ RENISHAW technical rep visited SBU with great advice!
- ▶ Absolute encoder desired to linear stage motion.
 - ▶ REQUIRES SPECIALIZED MOTOTR CONTROL UNIT.

FEATURES

- True absolute system
- Suitable for highly dynamic control loops
- Small footprint
- High accuracy
- Resolutions up to $0.244 \mu\text{m}$
- Axis lengths up to 16.3 m
- Speeds up to 7 m/s at $0.977 \mu\text{m}$ resolution
- Integral status LED
- Synchronous (SSI, SPI, BiSS) communication protocols available
- Parallel incremental output (analogue or digital)
- Double shielded, drag-chain compatible cable
- Simple and fast installation
- Robust measuring principle
- Excellent degree of protection to IP68



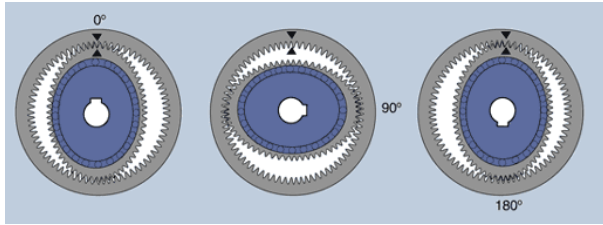
Absolute motor controller unit.



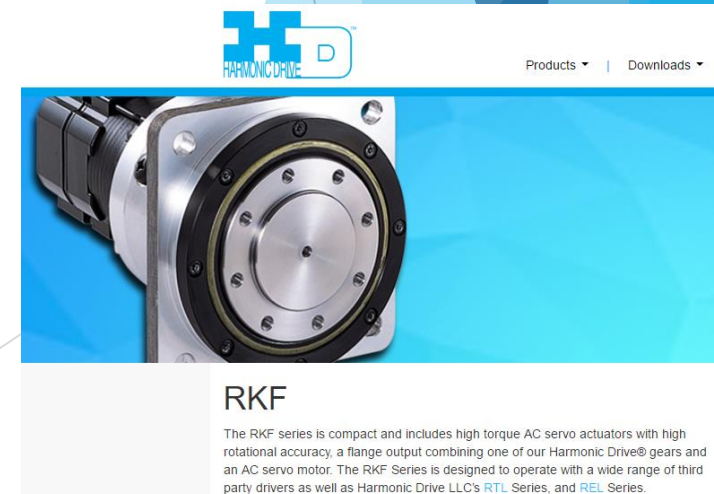
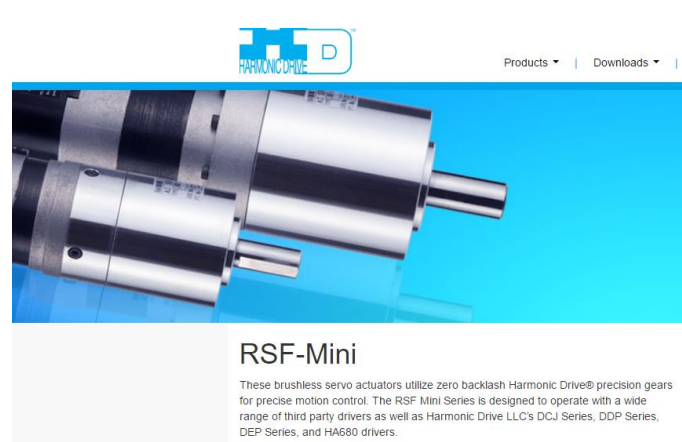
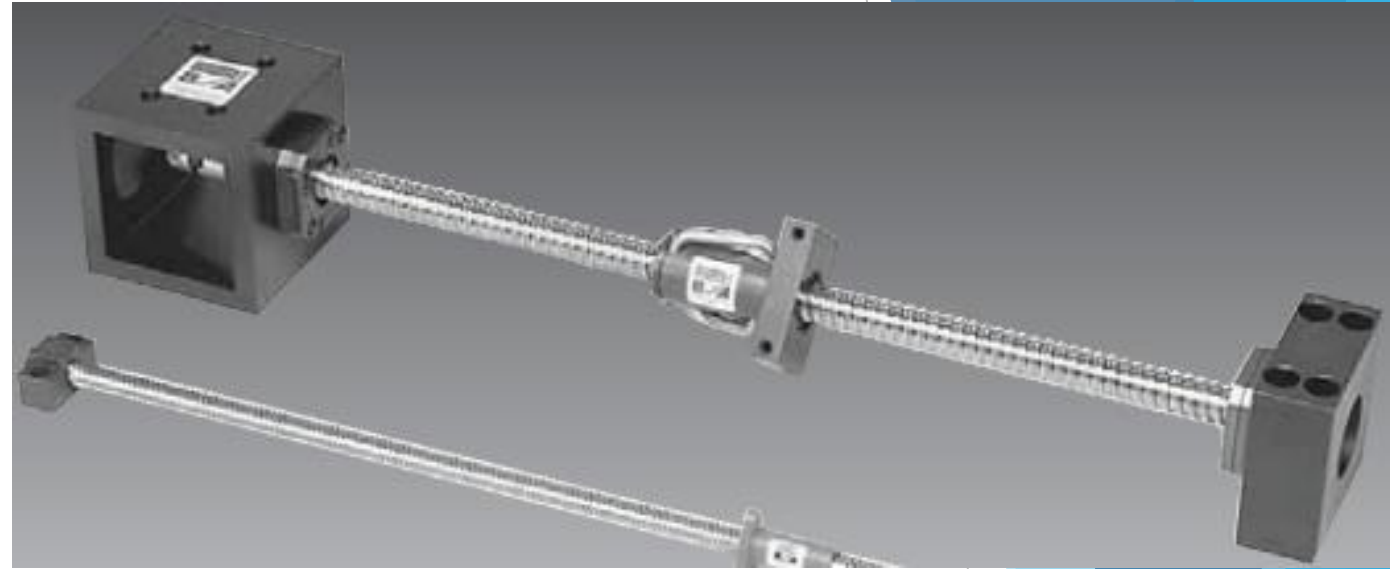
Accelnet Plus 1-Axis Panel

- ▶ Unit is VERY intelligent!
 - ▶ Accepts quadrature input for a standard shaft encoder (assuming motor/encoder pair).
 - ▶ Additionally accepts BISS interface for absolute position of stage.
- ▶ Engineer on phone was very interested in our application:
 - ▶ Recommends HARMONIC DRIVE MOTORS!

Harmonic Drive and Thomson Lead Screw



- ▶ Using all Harmonic Drive Motors:
 - ▶ Zero Backlash.
 - ▶ Internal geardown.
 - ▶ 30% teeth engaged.
 - ▶ High torque at very low RPM
- ▶ Linear position measured to $0.25\text{ }\mu\text{m}$.
- ▶ $r\phi$ position $100\text{ }\mu\text{m}$ at outer edge.

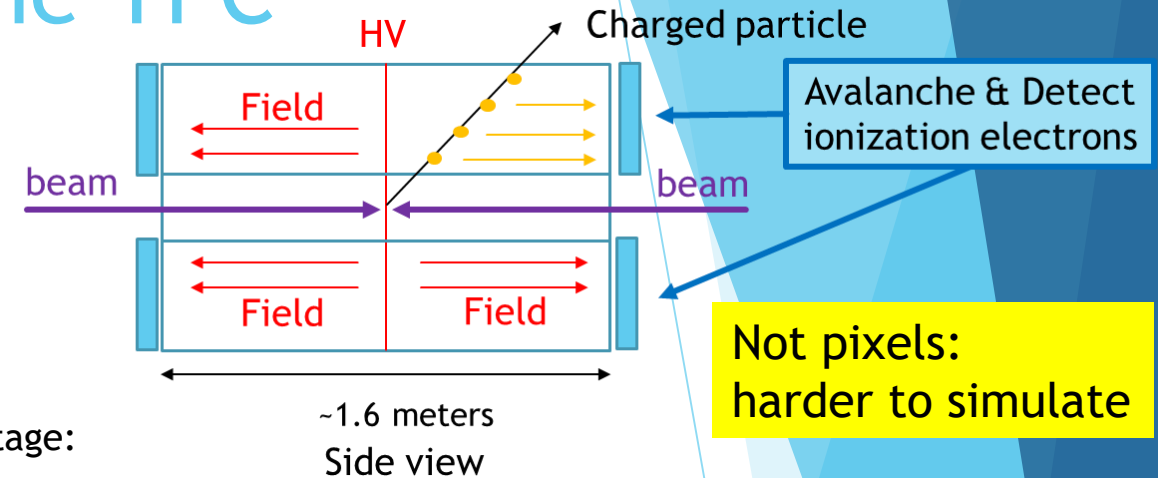


Summary

- ▶ Money from BNL arrived last Friday.
- ▶ Need to start spending some RSN.
- ▶ Outer radius spec: no change.
- ▶ Length spec settled including realistic sizes of avalanche stage.
- ▶ Table lengthens more than length spec to improve calibration and accuracy (site shaft)
- ▶ Better “foam” from speaking with engineer at general plastics.
- ▶ GOOD choices for motor, position feedback, and controller unit.
- ▶ Addition of termination mesh will improve detector performance as well as relax mechanical tolerances on things like the endplate.
- ▶ **MORE IMPORANTLY:** Termination mesh will decouple gain voltage from drift voltage!!

A Software-Oriented View of the TPC

- ▶ Hardware will still play a key role.
- ▶ Time-order of the physics dictates order of simulation:
 - ▶ Charged particle traverses gas leaving ionization trail.
 - ▶ Fluctuations in primary charge: $f(\text{GAS})$: well known
 - ▶ Electrons drift way from central membrane toward avalanche stage:
 - ▶ Transverse Diffusion: $f(\text{GAS}, \text{E-field}, \text{B-field})$: well known
 - ▶ Longitudinal Diffusion: $f(\text{GAS}, \text{E-field}, \{\text{B-field}\})$: well known
 - ▶ Drift Velocity: $f(\text{GAS}, \text{E-field}, \text{B-field})$: well known
 - ▶ Nominal Trajectory: $f(\text{GAS}, \text{E-field}, \text{B-field})$: well known
 - ▶ Space Charge Distortions:
 $f(\text{GAS}, \text{E-field}, \text{B-field}, \text{Avalanche Technology}, \text{rate}, \text{multiplicity}, \text{monitoring}, \text{readout})$: tools must be written by us!
- ▶ Existing simulations:
 - ▶ Driven principally by ILC-TPC R&D (test beam results)
 - ▶ Flaw: Wrong gas (bad for space charge).
 - ▶ Implements all “green” considerations except static B-field distortions.
 - ▶ Broken for everyone except Alan ☹; promised to be fixed today ☺ 5-19-2016.



What is the level of detail in current code?

Gas properties (Ar(95%) CF₄(3%) Isob(2%)), based on ILC prototype measurements and verified with Magboltz, ionization from PDG:

- $N_t = 38$ electrons/keV
- $v_{\text{drift}} \approx 6$ cm/ μ s at ~ 150 V/cm
- $D_t \approx 57$ μ m/ $\sqrt{\text{cm}}$ in 1.45 T field
- $w_t \approx 2.2$
- $X_0 \approx 11633$ cm

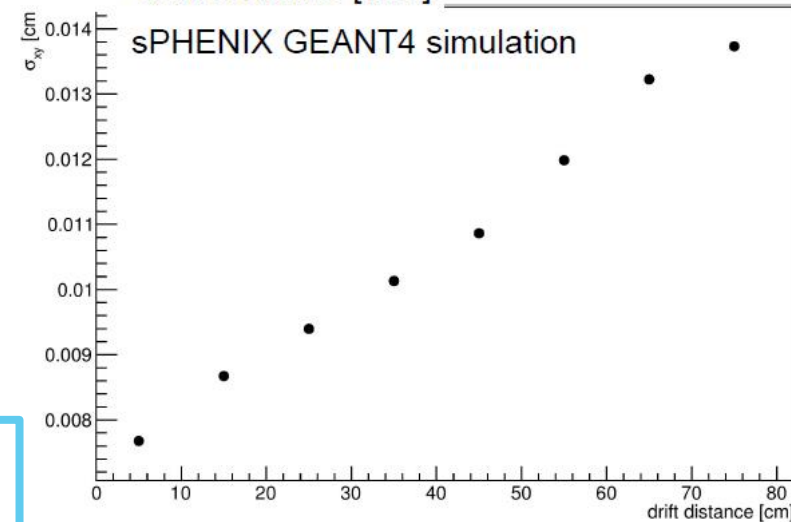
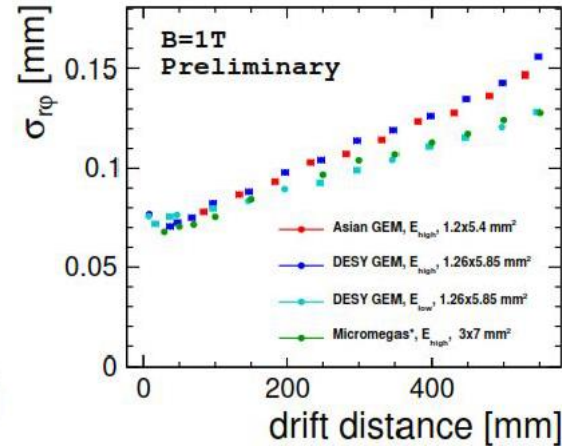
$$\sigma_{r\phi}^2 = \frac{D_t^2 z}{N_t} + \sigma_0^2$$

$$\sigma_z^2 = (1 + w_t^2) \frac{D_t^2 z}{N_t}$$

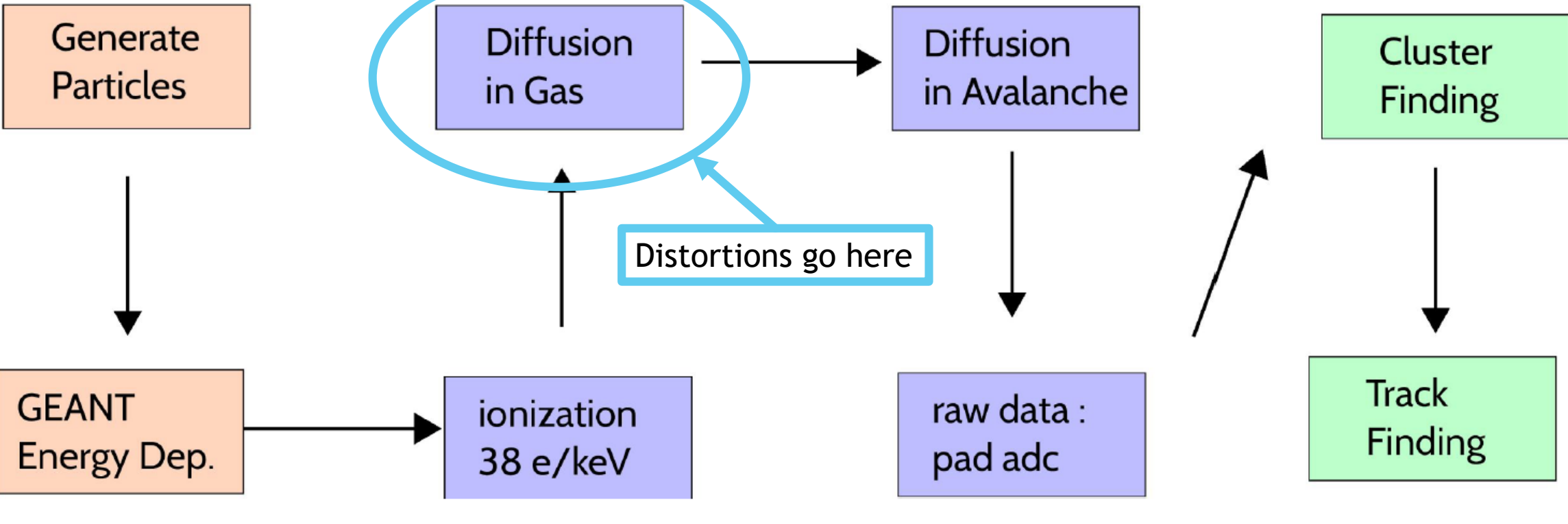
Charge sharing between 2-3 pads of 1.2mm, based on ILC prototype measurements:

- $\sigma_{\text{charge}} = 300$ μ m in triple GEM
- $\sigma_0 = 70$ -80 μ m

- ▶ Good realism for gas interactions/gain stage.
- ▶ Bad:
 - ▶ Wrong gas (too little diffusion)
 - ▶ No static B-field imperfections.
 - ▶ No space charge distortions included.

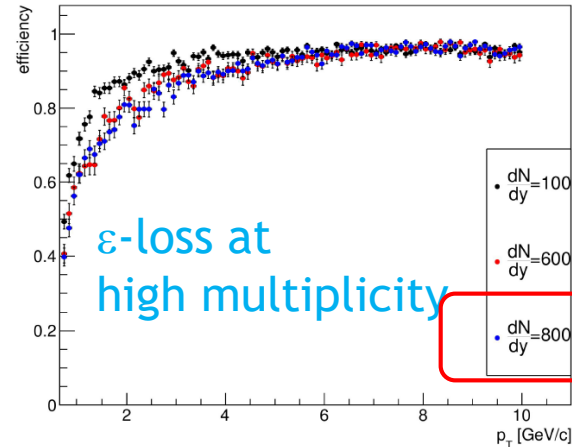
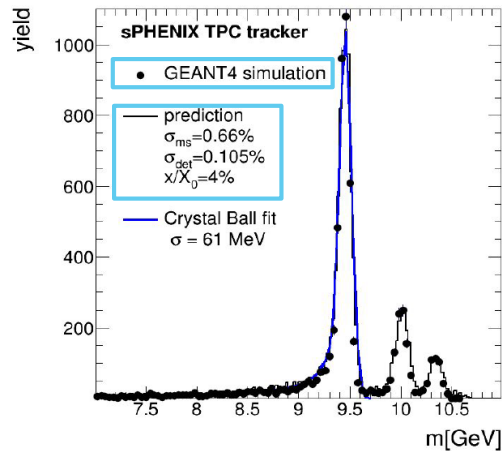


The chain as of now



Distortion-free mass resolution very good:

- Analytical same as G4 Simulation



$$\bullet \frac{dN}{dy} = 800$$

Present Status



Alan Dion

to hemmick, Carlos, Axel ▾

12:16 PM (30 minutes ago)



The main change was only at the macro level : the Hough transform needs to have UseCellSize set to true, as well as having the usual $\sqrt{12}$ passed as a scale between what the fitting sees and the pattern recognition sees as Hough size for the pixel layers. I am not sure how the macro and libraries got out of sync, but it is fixed.

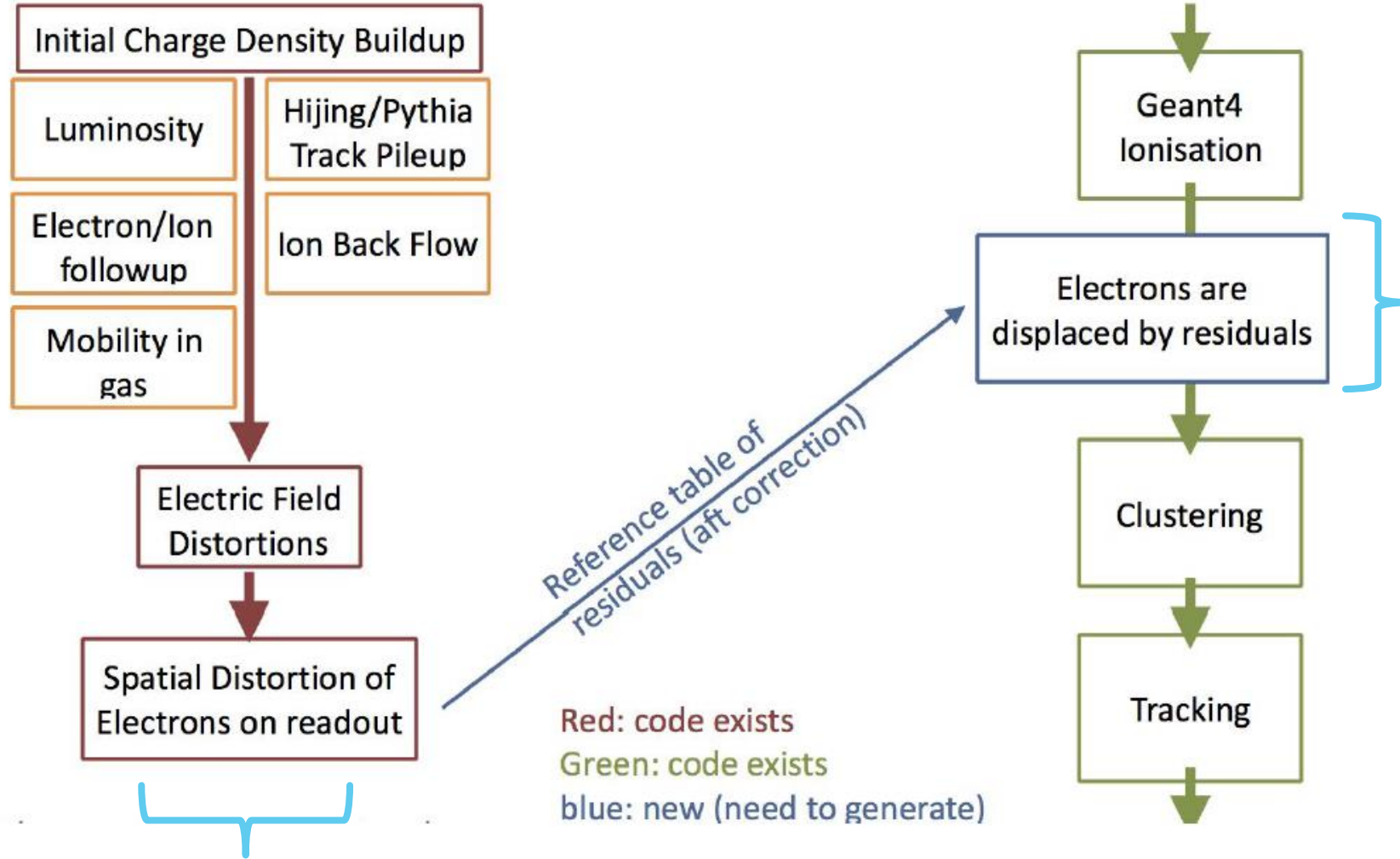
After that change to the macro only I could find tracks again.

I also modified the g4detectors library: I left a hard coded "2" as the number of pixel layers. I've changed that to a user input now, and all 3 maps layers are used correctly as far as I can tell.

I am not sure if Mike has run the code yet, but if I do a fresh checkout, compile g4detectors and helixhough, and set the macro to use maps+TPC, then I get tracks.

Mike McCumber: It seems that one speed limit is the memory usage of the Clusterizer.

Blue Boxes and Blue Lines



Here is where we put the “arbitrary” distortion

T. Frawley: *Please give me a handle on arbitrary distortion, we’ll calculate the limits.*

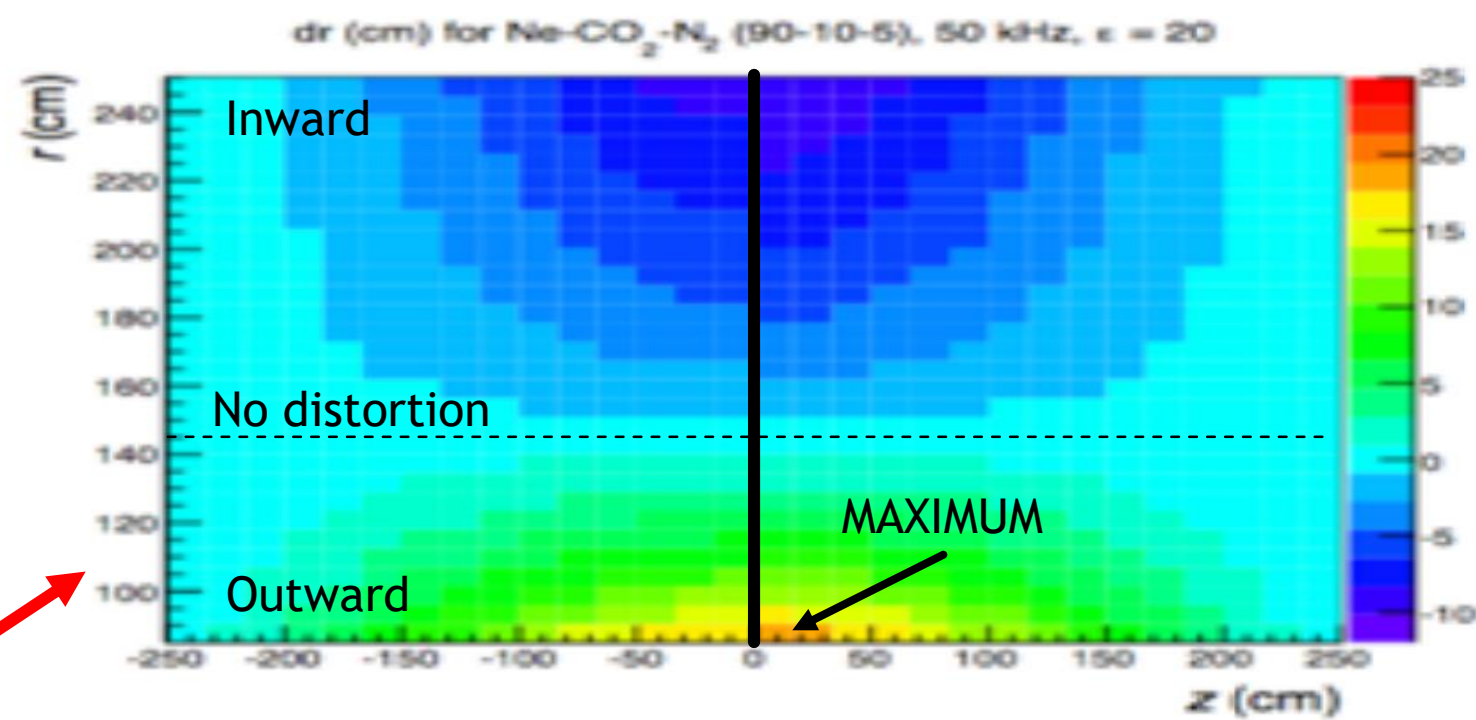
Here is where we put the “right” distortion

- What is the right distortion?
- Can we make a design that minimizes distortion

Tony's Hook

- ▶ Positive ions drift toward $z=0$.
- ▶ Pileup of old events linear in z .
- ▶ Maximum distortion:
 - ▶ $R = R_{\text{inner}}$
 - ▶ $Z = 0$.
- ▶ Maximum distortion value used as a reference:
 - ▶ ALICE: 20 cm
 - ▶ STAR: 10 cm
- ▶ Current Code:
 - ▶ Use the 2D (r, ϕ) distortion as reference:
 - ▶ PRECISION: $\text{sigma} = f1 * \text{DISTORTION}$
 - ▶ ACCURACY: $\text{delta} = f2 * \text{DISTORTION}$
 - ▶ Determine limits on $f1, f2$ to match KPP.
 - ▶ Compare to STAR/ALICE...

Requires 2D distortion map for sPHENIX!!



Mean Deflections of ionization due to space charge in ALICE @ 50 kHz

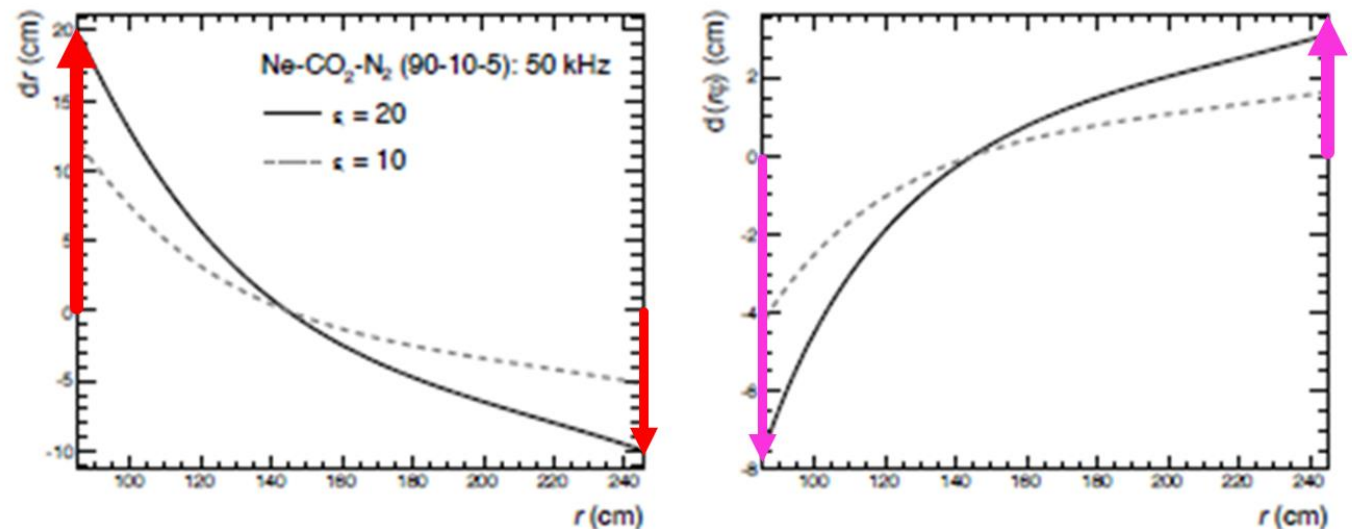


Figure 7.9: Space-point distortions in r (left panel) and $r\phi$ (right panel) as a function of the radial position r close to the central electrode ($z \approx 0$ cm) for Ne-CO₂-N₂ (90-10-5), $R_{\text{int}} = 50$ kHz, $\epsilon = 10$ and 20.

Plan to SC distortions reasonably quickly:

- ▶ PRECISION: $\sigma = f1 * \text{DISTORTION}$
- ▶ ACCURACY: $\delta = f2 * \text{DISTORTION}$

```
class SpaceChargeDistortion
{
public:
    SpaceChargeDistortion(const char * filename =
    virtual ~SpaceChargeDistortion() {}

    // For this analysis we only use Init, proce
    double dr (double r, double phi, double z);
    double drPhi (double r, double phi, double z);

    //
    void setPrecision(double p) {precisionFactor
    void setAccuracy (double a) { accuracyFactor
```

sPHENIX20

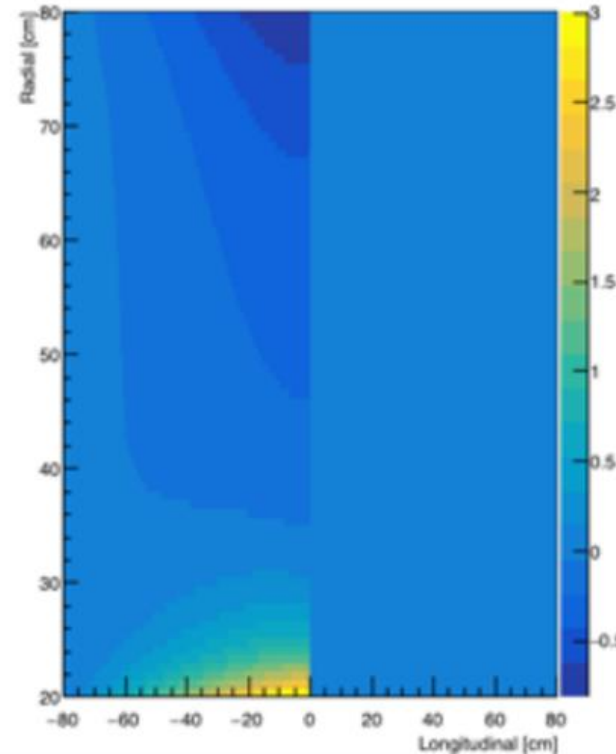
Grid size:

Rad = 0.75 cm

Phi = 360 deg

Lon = 0.64 cm

δ_r [cm]



sPHENIX30

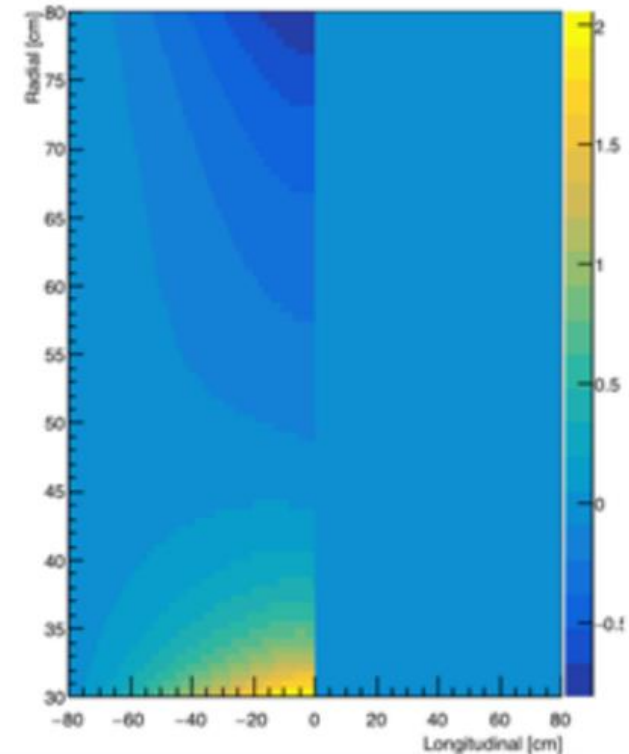
Grid size:

Rad = 0.63 cm

Phi = 360 deg

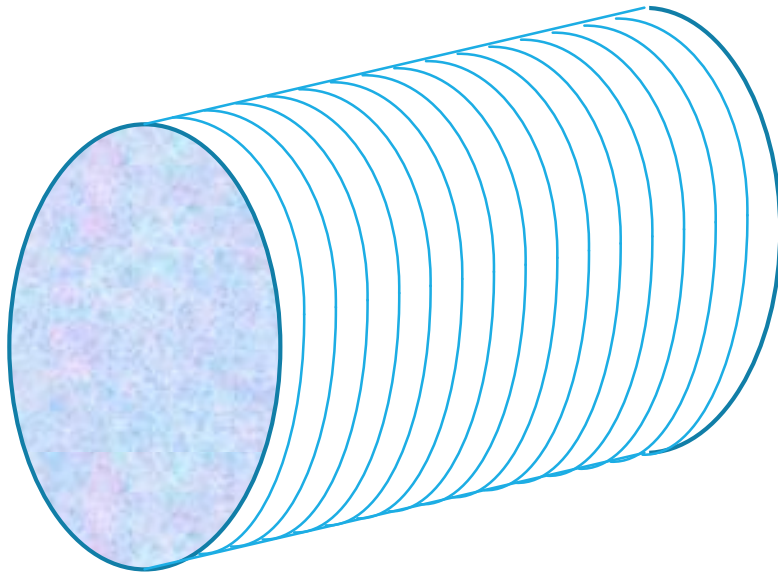
Lon = 0.64 cm

δ_r [cm]

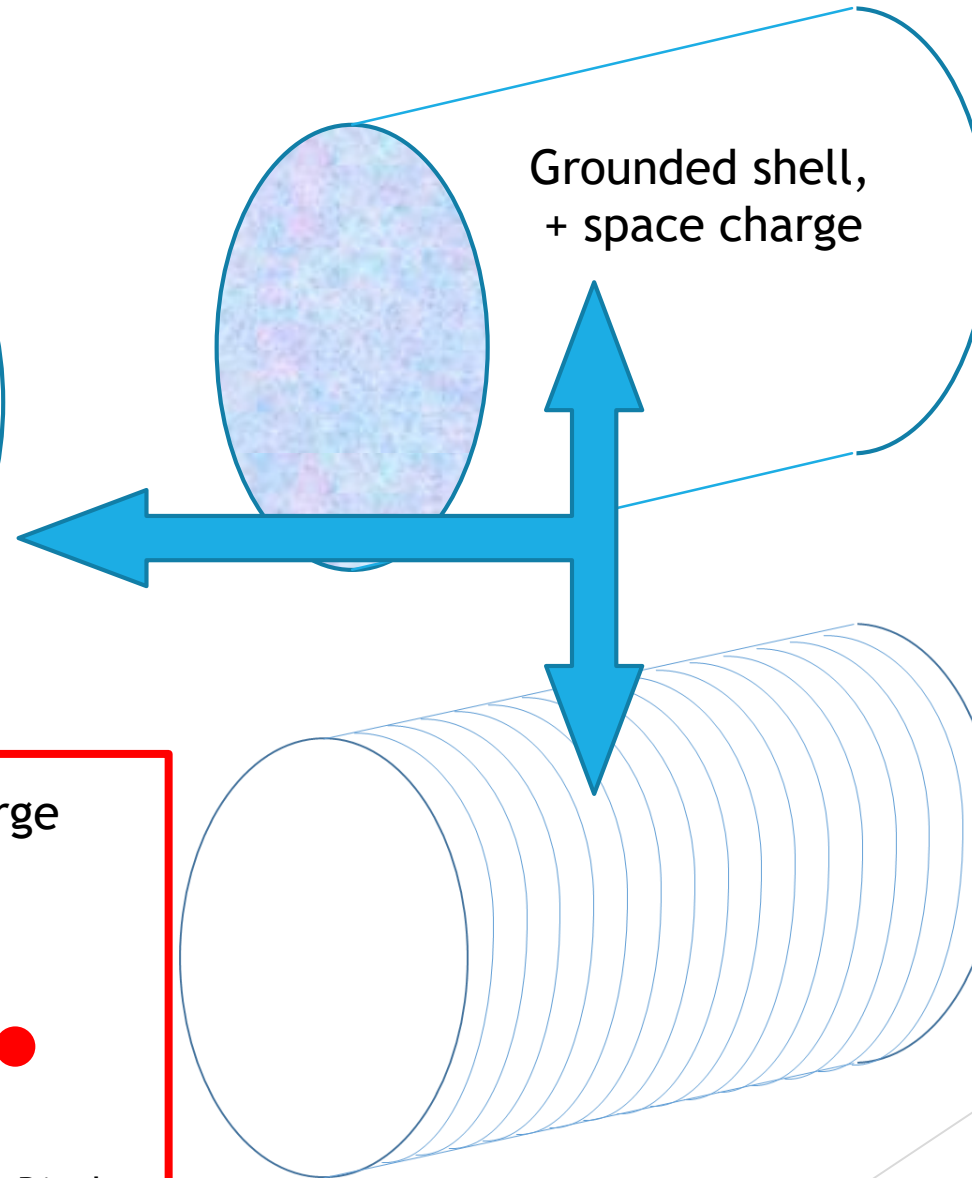


Factorization of the Space Charge Problem

Cylinder with graded potentials and space charge in the volume



Grounded shell,
+ space charge



- ▶ Graded field cage field determined by ANSYS or COLSOL finite element calculations.

- ▶ Grounded shell solved using Greene's theorem

$$\Delta G(\vec{r}, \vec{r}_{ch}) = \delta(\vec{r} - \vec{r}_{ch})$$

$$\vec{E}_{ch}(\vec{r}, \vec{r}_{ch}) = \vec{\nabla} G(\vec{r}, \vec{r}_{ch})$$

$$\vec{E} = \int \rho(\vec{r}_{ch}) \vec{E}_{ch}(\vec{r}, \vec{r}_{ch}) dV_{ch}$$

Point + Sheet

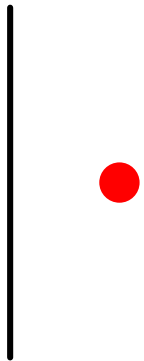
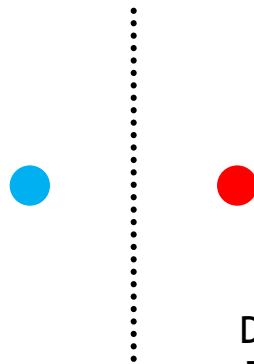


Image Charge



Dipole
Field!

Graded potentials, no charge

Carlos

Tom

Finishing the solution

- Once the solutions to the homogeneous equation are known, we express the Dirac delta function in this basis:

$$\delta(\phi - \phi') = \frac{1}{2\pi} \sum_{m=-\infty}^{\infty} e^{im(\phi - \phi')} = \frac{1}{2\pi} \sum_{m=0}^{\infty} (2 - \delta_{m0}) \cos[m(\phi - \phi')],$$

$$\frac{\delta(r - r')}{r} = \sum_{n=1}^{\infty} \frac{R_{mn}(r) R_{mn}(r')}{N_{mn}^2} \quad \text{with} \quad N_{mn}^2 = \int_a^b R_{mn}^2(r) r dr,$$

$$m = 0, 1, 2, \dots$$

- After which the solution is readily obtained:

$$G(r, \phi, z; r', \phi', z') = \frac{1}{2\pi} \sum_{m=0}^{\infty} \sum_{n=1}^{\infty} (2 - \delta_{m0}) \cos[m(\phi - \phi')] \frac{R_{mn}(r) R_{mn}(r')}{N_{mn}^2} \frac{\sinh(\beta_{mn} z_{<}) \sinh(\beta_{mn} (L - z_{>}))}{\beta_{mn} \sinh(\beta_{mn} L)},$$

- Although the solution is correct, it is not assured to be readily convergent.
- Rossegger used three independent basis sets to obtain stable, differentiable, convergent solutions for the r , ϕ , and z components of the field:

$$\frac{\partial}{\partial z} G(r, \phi, z, r', \phi', z') = \frac{1}{2\pi} \sum_{m=0}^{\infty} \sum_{n=1}^{\infty} (2 - \delta_{m0}) \cos[m(\phi - \phi')] \frac{R_{mn}(r) R_{mn}(r')}{N_{mn}^2} \frac{\partial}{\partial z} \left(\frac{\sinh(\beta_{mn} z_{<}) \sinh(\beta_{mn} (L - z_{>}))}{\beta_{mn} \sinh(\beta_{mn} L)} \right), \quad (5.64)$$

$$\text{with} \quad \frac{\partial}{\partial z} (\sinh(\beta_{mn} z_{<}) \sinh(\beta_{mn} (L - z_{>}))) = \begin{cases} \beta_{mn} \cosh(\beta_{mn} z) \sinh(\beta_{mn} (L - z')), & \text{for } 0 \leq z < z' \leq L, \\ -\beta_{mn} \cosh(\beta_{mn} (L - z)) \sinh(\beta_{mn} z'), & \text{for } 0 \leq z' < z \leq L. \end{cases}$$

$$\frac{\partial}{\partial r} G(r, \phi, z, r', \phi', z') = \frac{1}{\pi L} \sum_{m=0}^{\infty} \sum_{n=1}^{\infty} (2 - \delta_{m0}) \cos[m(\phi - \phi')] \sin(\beta_n z) \sin(\beta_n z') \frac{\partial}{\partial r} \left(\frac{R_{mn1}(r_{<}) R_{mn2}(r_{>})}{I_m(\beta_n a) K_m(\beta_n b) - I_m(\beta_n b) K_m(\beta_n a)} \right), \quad (5.65)$$

$$\text{with} \quad \frac{\partial}{\partial r} (R_{mn1}(r_{<}) R_{mn2}(r_{>})) = \begin{cases} R'_{mn1}(a, r) R_{mn2}(r'), & \text{for } a \leq r < r' \leq b, \\ R_{mn1}(r') R'_{mn2}(b, r), & \text{for } a \leq r' < r \leq b, \end{cases}$$

wherein $R'_{mn}(s, t)$ is

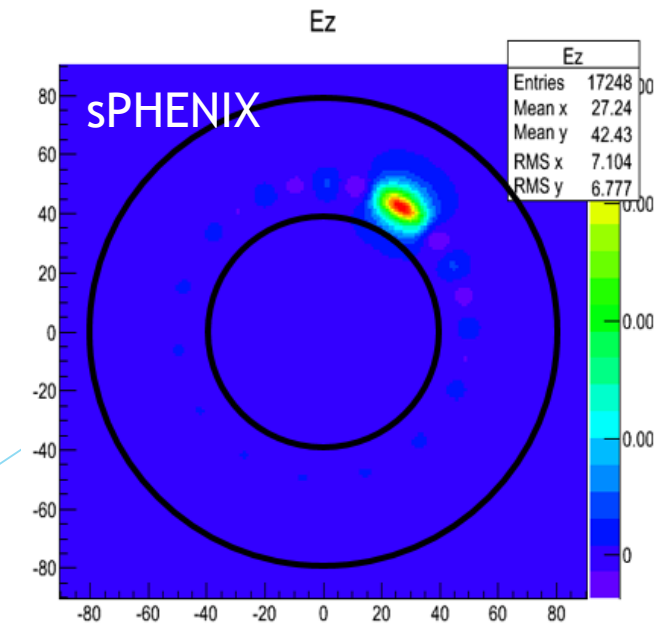
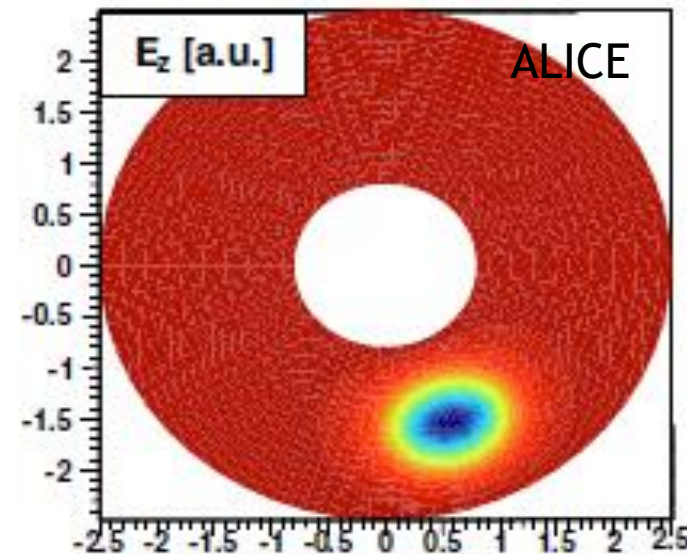
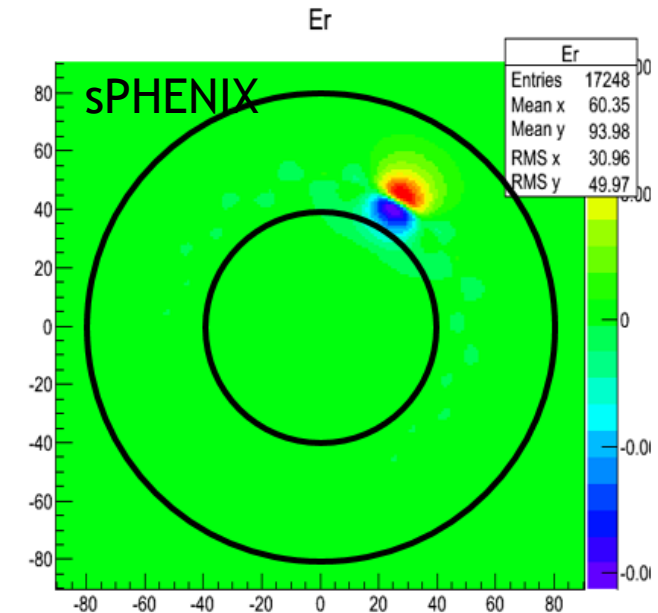
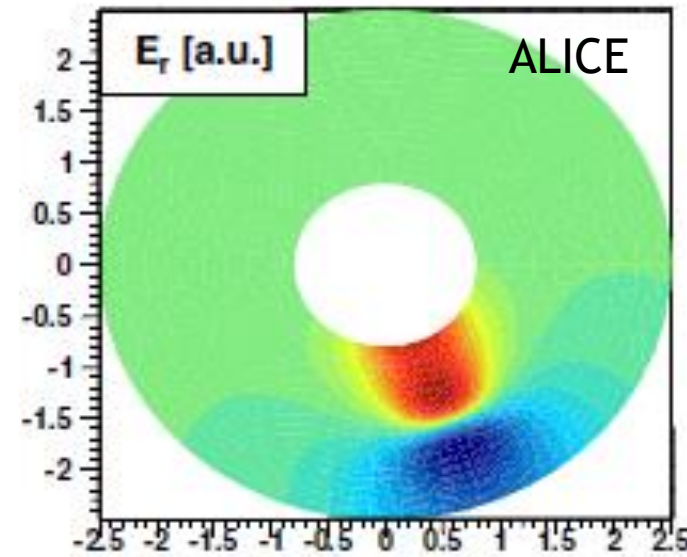
$$R'_{mn}(s, t) = \frac{\beta_n}{2} (K_m(\beta_n s) (I_{m-1}(\beta_n t) + I_{m+1}(\beta_n t)) + I_m(\beta_n s) (K_{m-1}(\beta_n t) + K_{m+1}(\beta_n t))).$$

$$\frac{\partial}{\partial \phi} G(r, \phi, z, r', \phi', z') = \frac{1}{L} \sum_{k=1}^{\infty} \sum_{n=1}^{\infty} \sin(\beta_n z) \sin(\beta_n z') \frac{R_{nk}(r) R_{nk}(r')}{N_{nk}^2} \frac{\partial}{\partial \phi} \left(\frac{\cosh[\mu_{nk}(\pi - |\phi - \phi'|)]}{\mu_{nk} \sinh(\pi \mu_{nk})} \right) \quad (5.66)$$

$$\text{with} \quad \frac{\partial}{\partial \phi} (\cosh[\mu_{nk}(\pi - |\phi - \phi'|)]) = \begin{cases} -\mu_{nk} \sinh[\mu_{nk}(\pi - (\phi - \phi'))], & \text{for } 0 \leq \phi' < \phi \leq 2\pi \\ \mu_{nk} \sinh[\mu_{nk}(\pi - (\phi' - \phi))], & \text{for } 0 \leq \phi < \phi' \leq 2\pi \end{cases}$$

“Sanity Check”

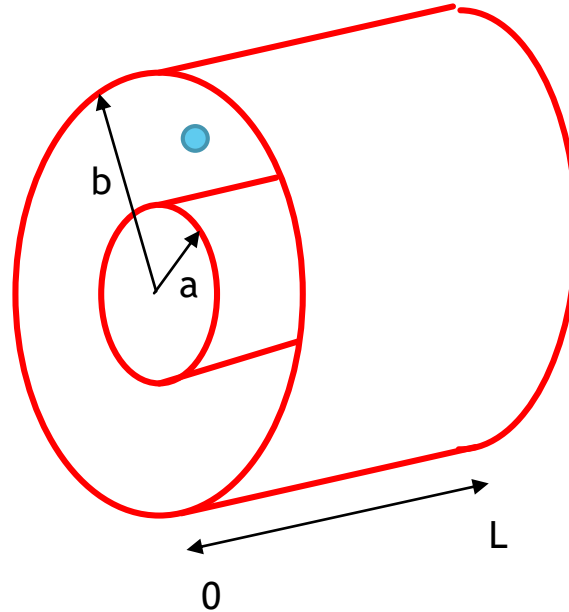
- ▶ Basic shape of the field components looks very similar to ALICE and matches physical intuition.
- ▶ This is not yet proof that the implementation of the functions is:
 - ▶ Robustly correct.
 - ▶ Produces an answer on a known scale (V/cm is neither mks nor cgs).
- ▶ Test the implementation by confirming that the result obeys Gauss' Law!



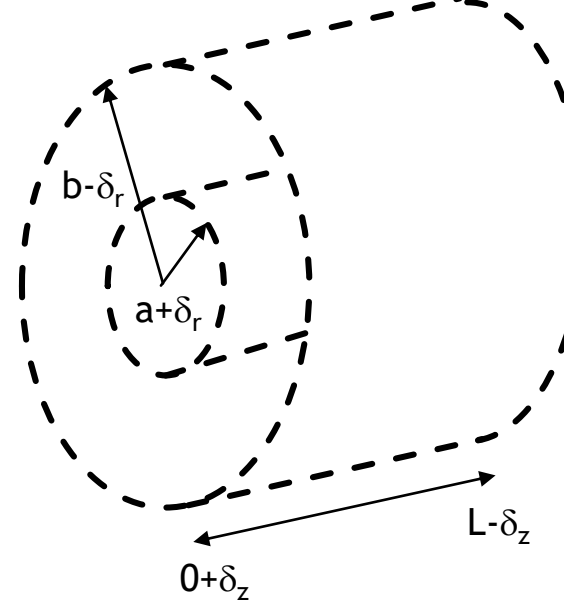
Gauss' Law Test

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{in}}{\epsilon_0}$$

TPC Boundaries



Gaussian Surface



▶ Place single point charge.

▶ Gaussian surface “interior” by δ_r and by δ_z .

▶ Integrate Gauss' Law vs δ_r and by δ_z .

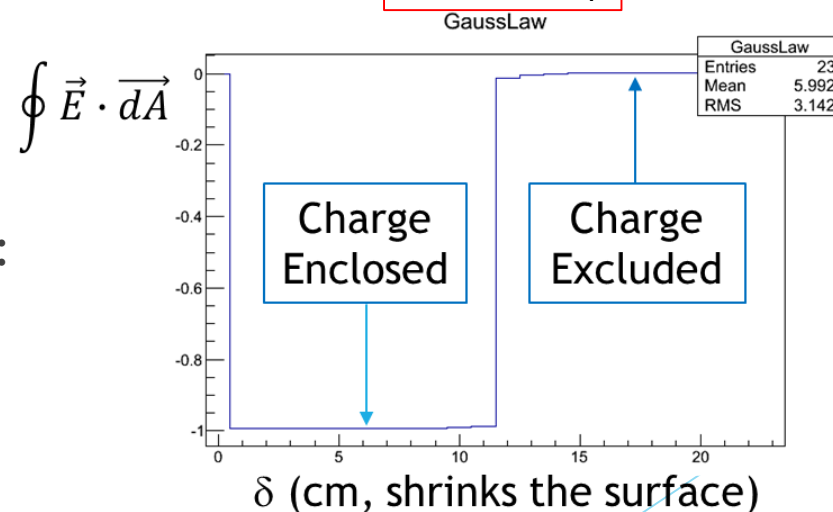
▶ Expectation:

- ▶ Constant while charge enclosed.
- ▶ Zero when charge excluded.

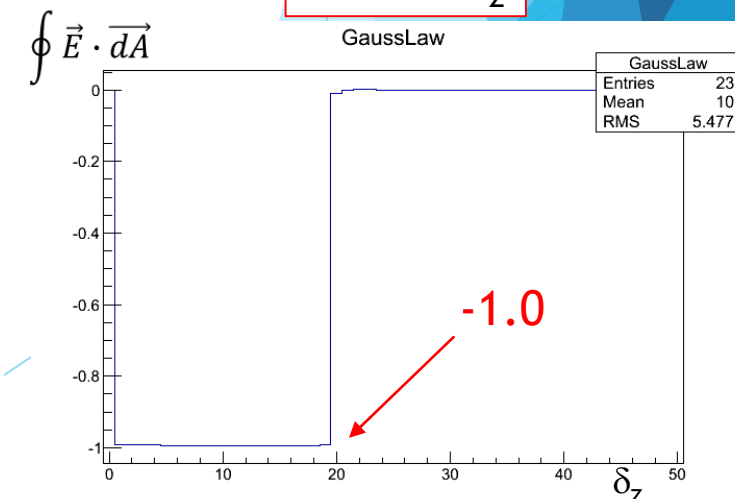
▶ Integral negative due to dropping minus:

$$\vec{E} = \ominus \vec{\nabla} V$$

Test of E_r



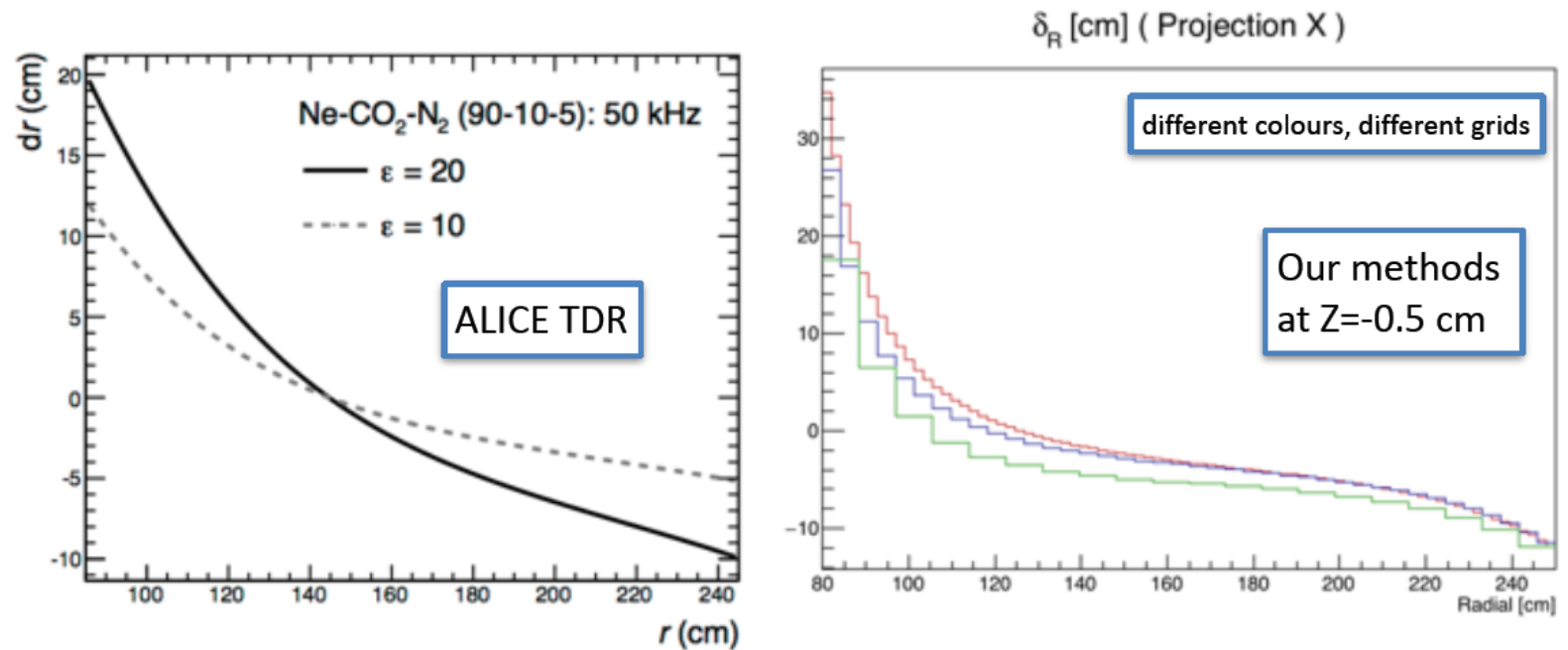
Test of E_z



Comparison to ALICE

- ▶ Reasonable agreement of “our ALICE” with the ALICE TDR.
- ▶ Some details of the calculation are different, but these don't seem major.

Dr detailed shape comparison



Quantitatively close, but not quite the right shape

Source of incongruence:

- We do Laplace expansion up to 15th order (ALICE 30th)
- We probe Dr at $z=-0.5$ cm (ALICE gets it at $z=0$)
- We use $1/r^2$ in ICD (ALICE used $1/r^{1.5}$ for TDR)

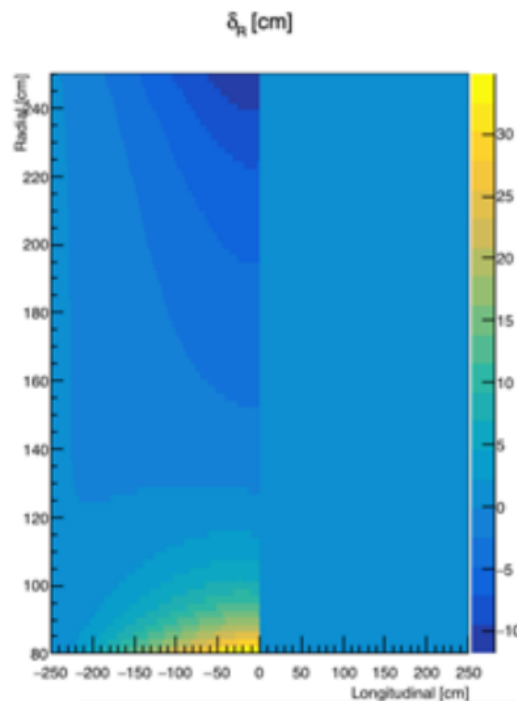
Calculations for sPHENIX

- ▶ Calculations for ALICE (reference)
- ▶ sPHENIX with 30 cm inner radius
- ▶ sPHENIX with 20 cm inner radius
- ▶ Concept:
 - ▶ Instrument from 30-80 cm.
 - ▶ Use “extra charge” to minimize space charge distortion of innermost point.
- ▶ Use the sPHENIX20 and sPHENIX30 as input distributions to “Tony’s Hook”.

Estimated mean distortions in R

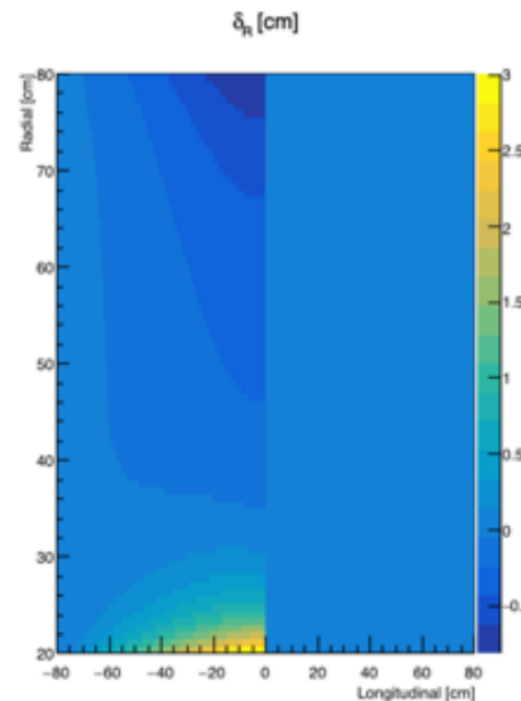
ALICE

Grid size:
Rad = 2.13 cm
Phi = 360 deg
Lon = 2 cm



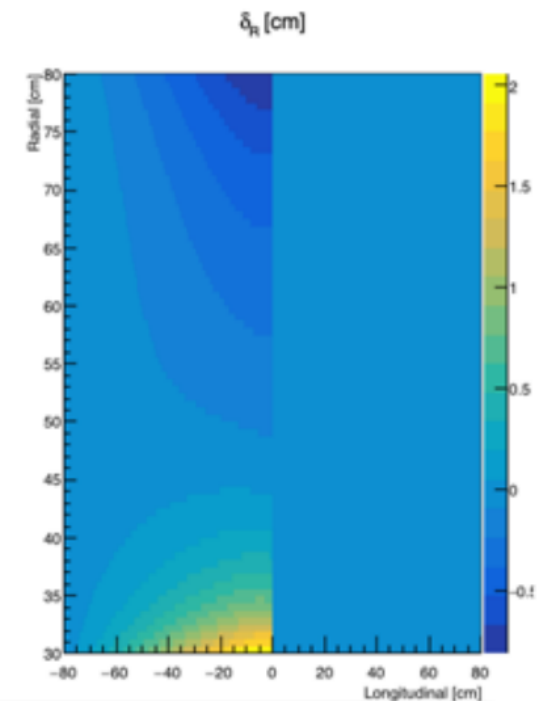
sPHENIX20

Grid size:
Rad = 0.75 cm
Phi = 360 deg
Lon = 0.64 cm



sPHENIX30

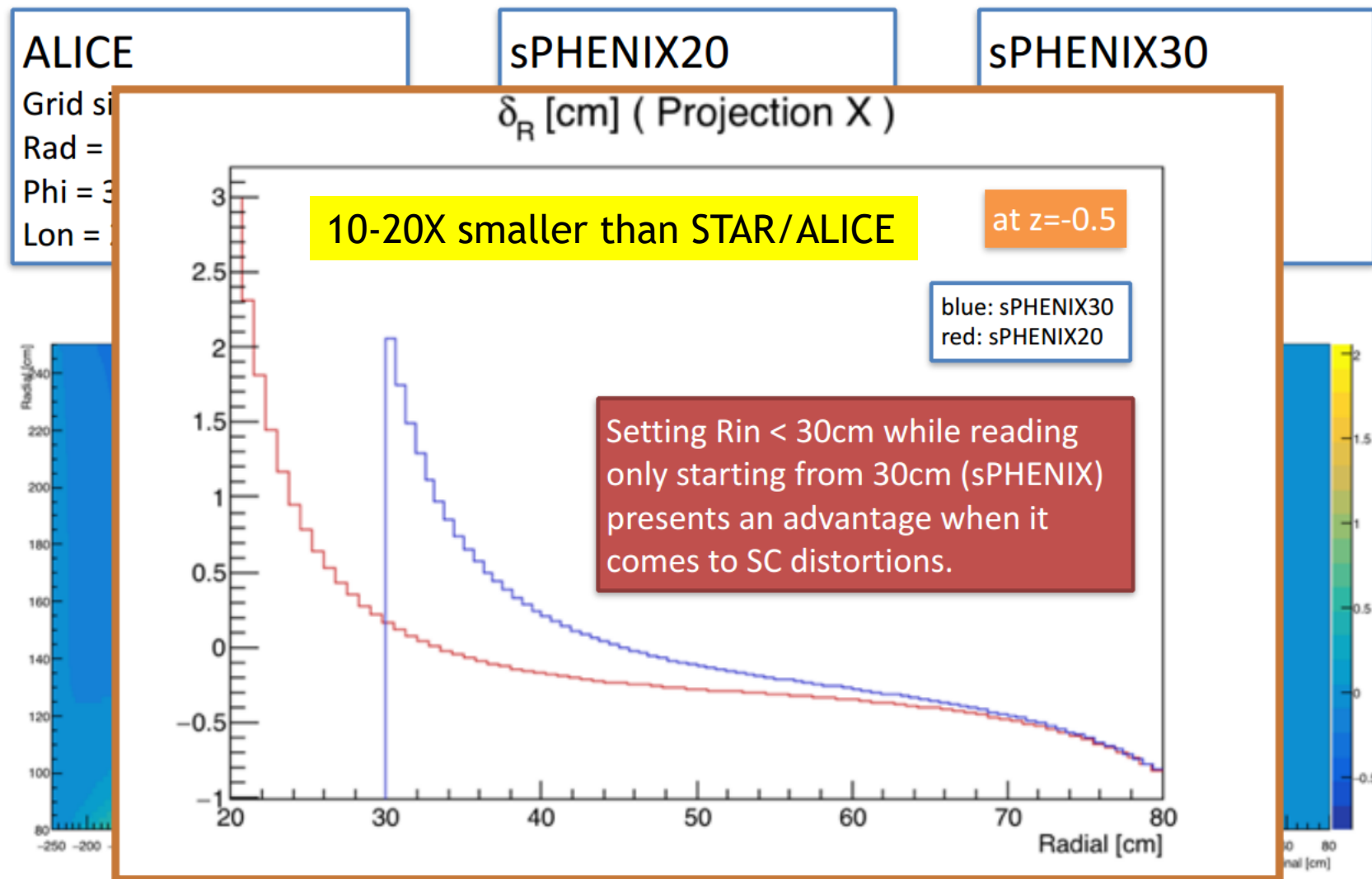
Grid size:
Rad = 0.63 cm
Phi = 360 deg
Lon = 0.64 cm



The inner radius effect:

- ▶ The effect of moving the inner radius in is significant, moving the inner-most space point distortion to roughly 2mm.
- ▶ Outer radius becomes the most significant distortion which becomes ~ 8mm.
- ▶ Further reductions in IBF are not yet applied for these calculations.
- ▶ Non-space charge systematic errors are likely the dominant source of systematic error.

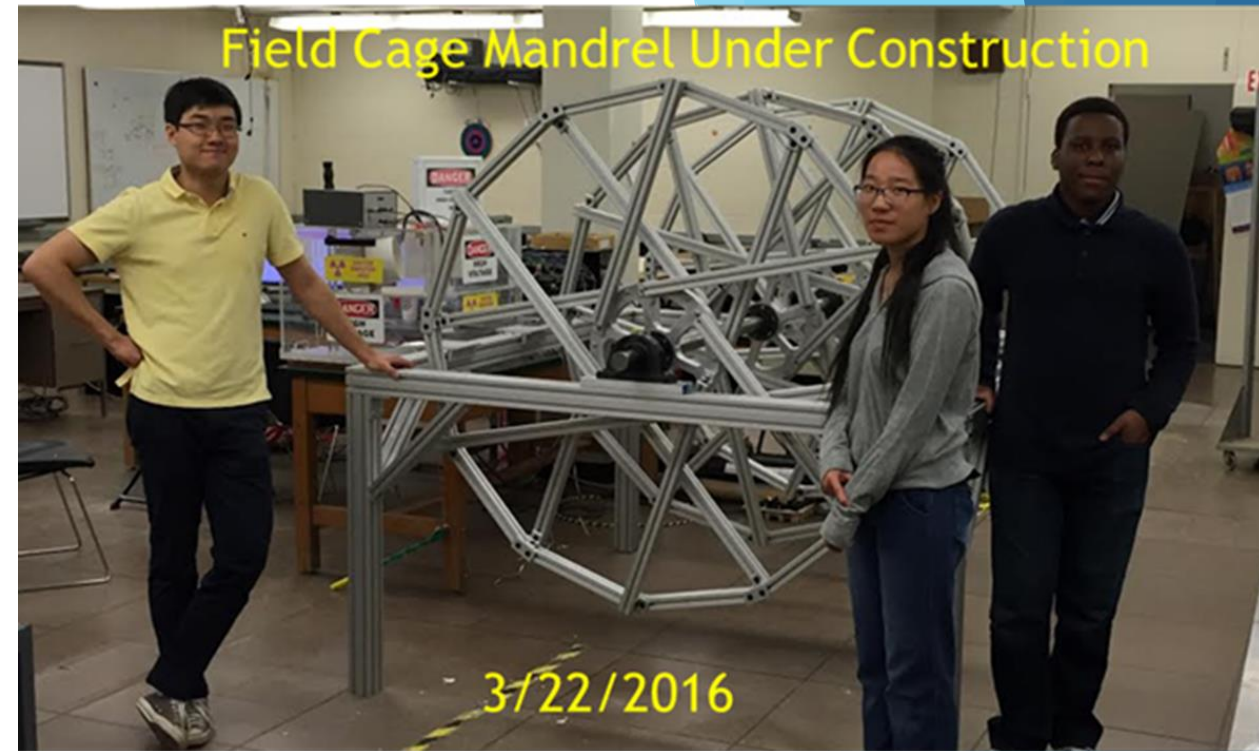
Estimated mean distortions in R



HARDWARE PROGRESS

Prototyping R&D Strategy

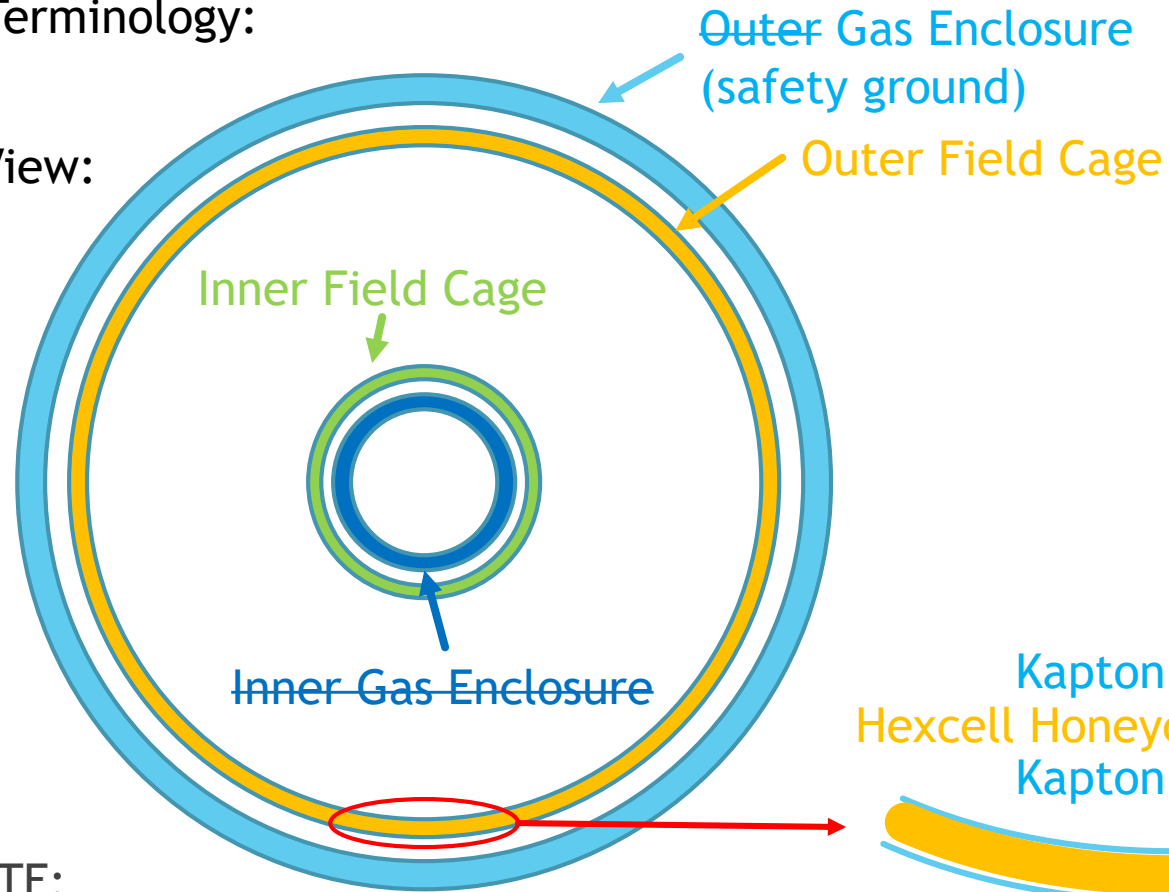
- ▶ Build full sized field cage during the R&D cycle.
 - ▶ Use this field cage for the actual experiment.
 - ▶ “Hidden Cost Savings”
 - ▶ 0 cost, 0 overhead 0 contingency.
 - ▶ Allows us to test gain stages at full size (MPGD reliability can be issue at large size)
- ▶ Requires INTENSIVE R&D IMMEDIATELY.
 - ▶ Voltage holding, mechanical strength, electrode precision, flatness, ...
- ▶ So, we’re doing that...since even the field cage requires clever design.



Cartoons for terminology

STAR Terminology:

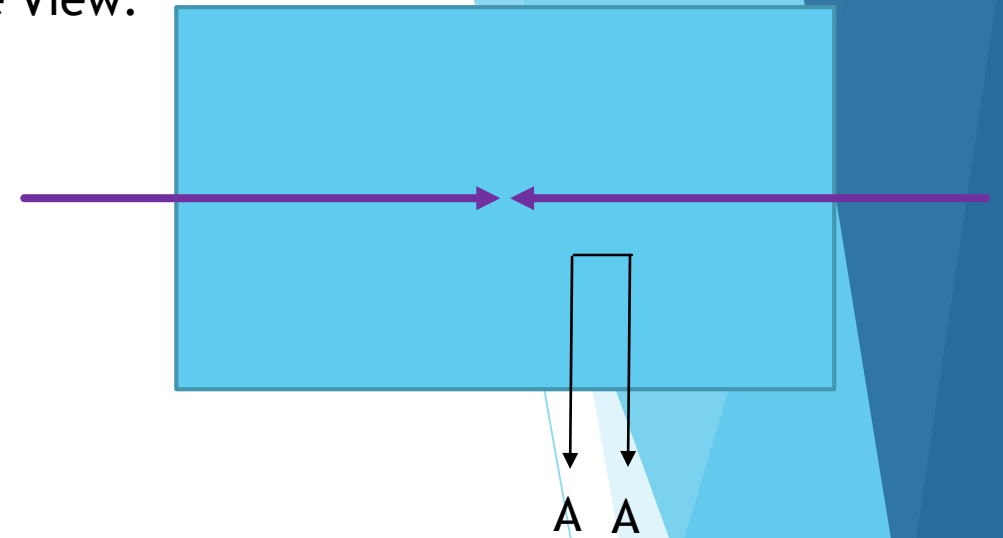
End View:



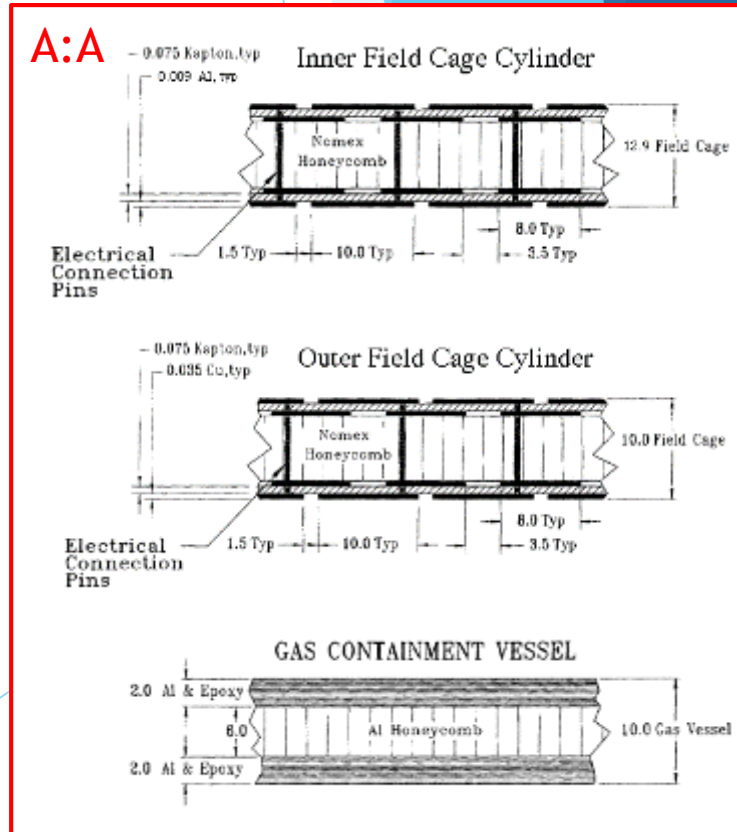
NOTE:

- ▶ STAR skipper the inner gas enclosure.
- ▶ Advice: Don't copy that mistake.

Side View:



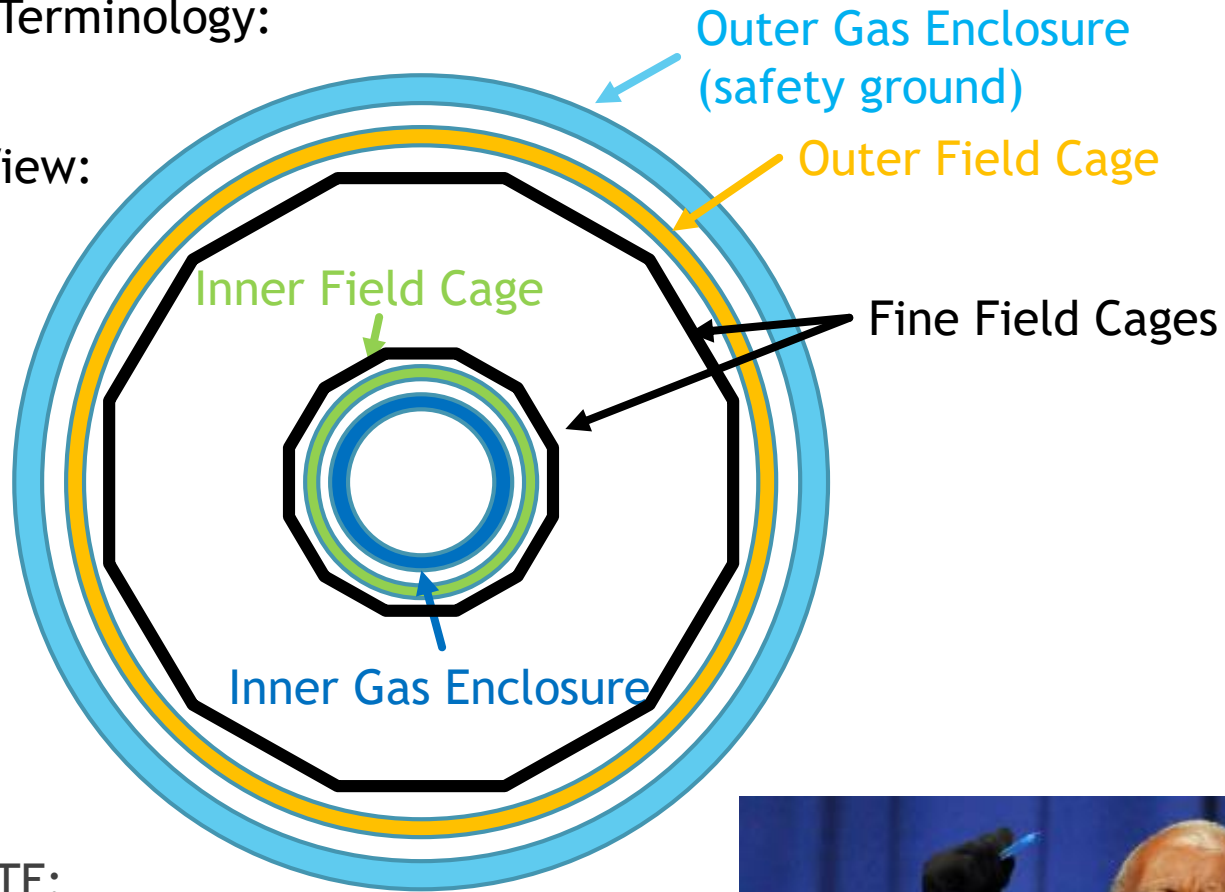
Kapton or FR4
Hexcell Honeycomb (1cm - 1/2")
Kapton or FR4



More Cartoons for terminology

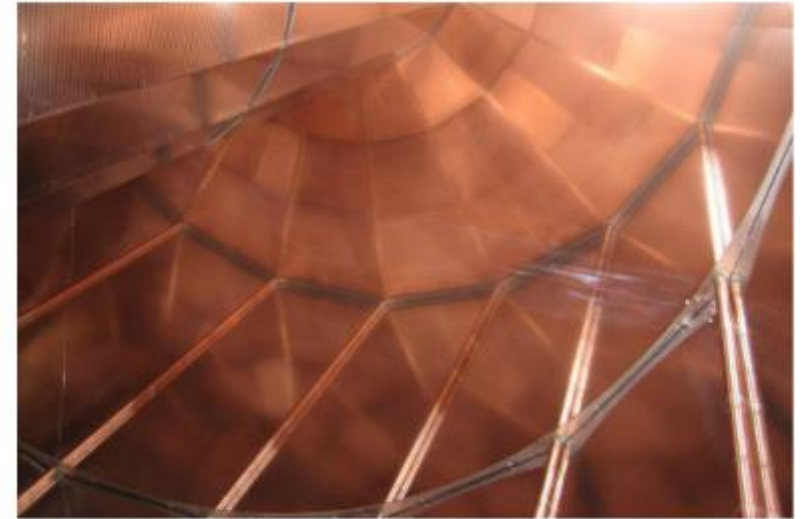
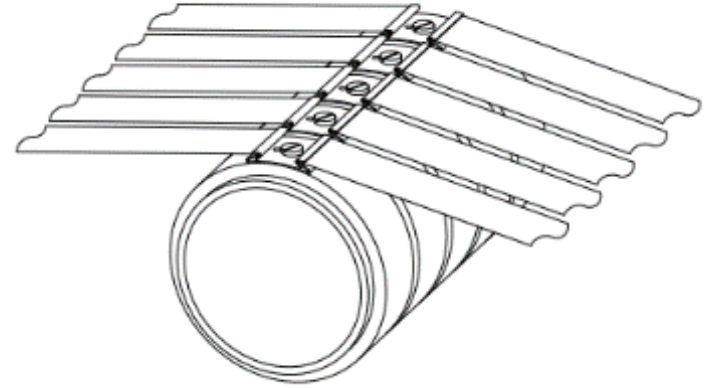
ALICE Terminology:

End View:



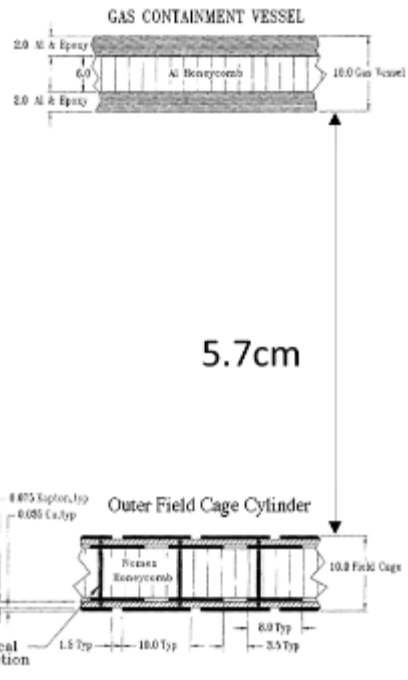
NOTE:

- ▶ ALICE adds fine field cage.
- ▶ We don't have room!



Fine Field Cages use too much damn room

STAR uses an air gap:



Drawing **IS** to scale.

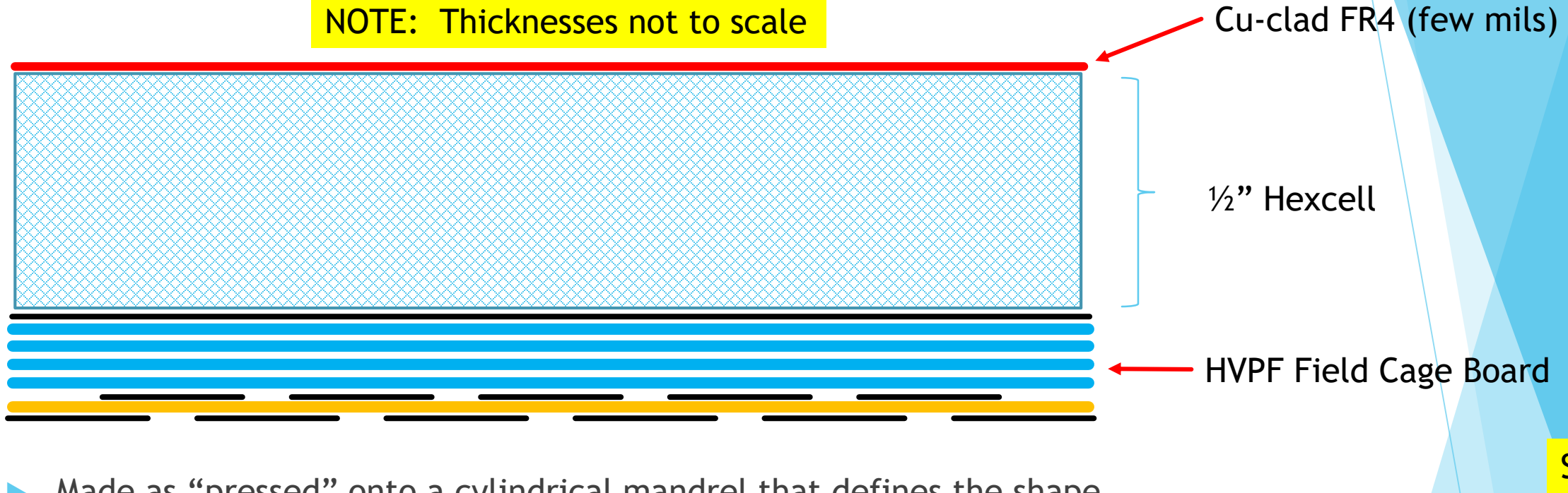
- ▶ STAR used a 5.7 cm gap holding a maximum voltage of 27 kV.
- ▶ They flowed nitrogen through the gap.
- ▶ Overall thickness is 7.7cm.
- ▶ Using the same considerations, we would design:
 - ▶ $Gap = 5.7cm \frac{34000\text{ Volt}}{27000\text{ Volt}} = 7.2\text{ cm}$
 - ▶ With 1cm for each honeycomb = 9.2 cm.
 - ▶ This is 3.6 inches (4X too large).

A BIG TPC (ours will be smaller)

Losing 7-9 cm in a device this big is OK for STAR...but not for us!

Design concept for full field cage.

NOTE: Thicknesses not to scale



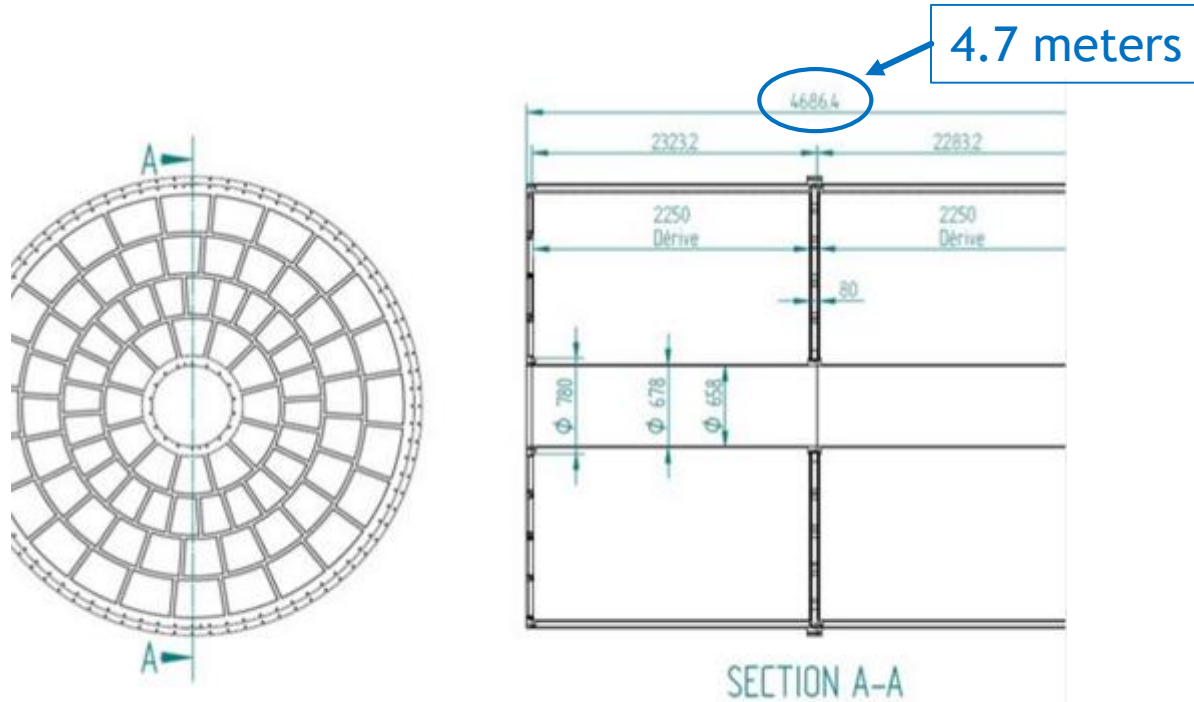
- ▶ Made as “pressed” onto a cylindrical mandrel that defines the shape.
- ▶ 1mm of kapton is ~0.3% of a radiation length.
- ▶ Shielded HV cable that holds 100 kV is 0.4” diameter (fits inside hexcell).
- ▶ Resistor chain inside the gas (like STAR & ILC).
- ▶ Test a flat prototype in the tandem injector cage.

Figure 11: Materials Supported in Multilayer High Voltage

Material Type	Max. Operating Temperature (°C)	T/G °C	Voltage (V/mil) Note 1	Aged rating (V/mil)	W°C/m
FR4	105-130	160	800	300/150	0.21
FR4 Hi-Temp.	130-150	170	800	300/150	0.22
BT Epoxy	140-160	180	1300	600/400	0.40
Polyimide	150-190	200	900	700/500	0.25
HVPF*	180-200	210	3000 to 7000	3000/2000	0.28

*HVPF is a trademark of Sierra proto express.

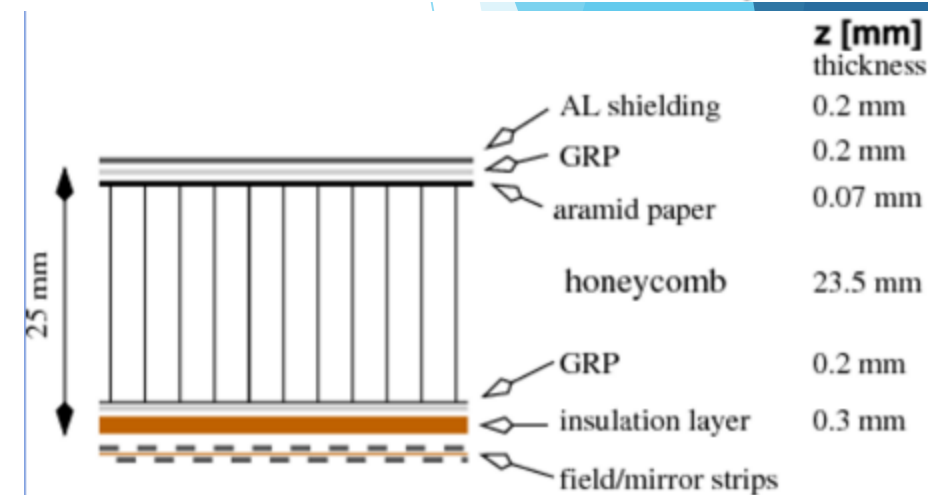
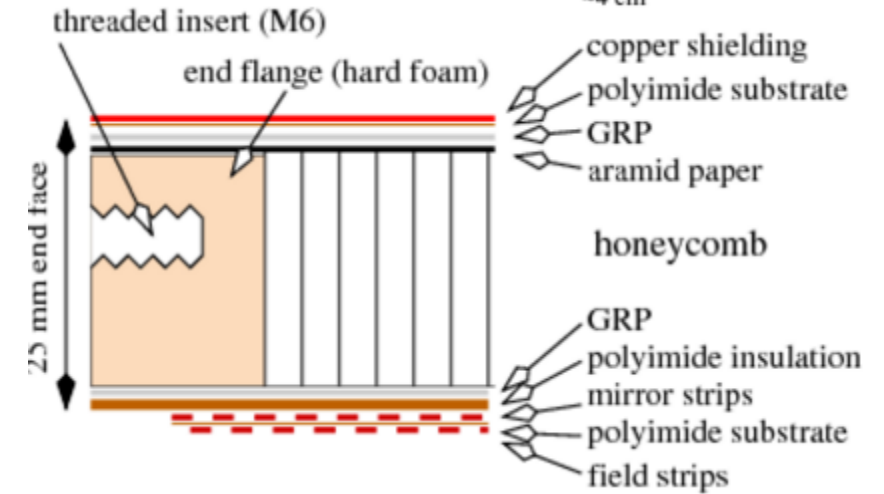
VERY similar to ILC:



- ▶ Sized between STAR & ALICE.
- ▶ Does not use the “fine field cage”.
- ▶ Combines the field cage & gas enclosure into a single layer.

CONCLUSION:

- Our design will be a field cage and ground layer as a single unit.
- Need R&D for the specifics of the design...



HV test card design

Board shall be named "TPC HV TB-Rev 0"

Flexible

1. Test to destruction.
2. Irradiate...test again.

Multiple layers
3-4 mils per layer
Kapton adhesive/kapton layers
Laminated to final thickness.
Etch out the copper
Followed by ENIG

0.5 Oz Cu

HVPF

1 mm +/- 10%

Gerber files...

30 pieces
50 pieces.
Turn time 10 days
8" by 8"
No vias

8 inches

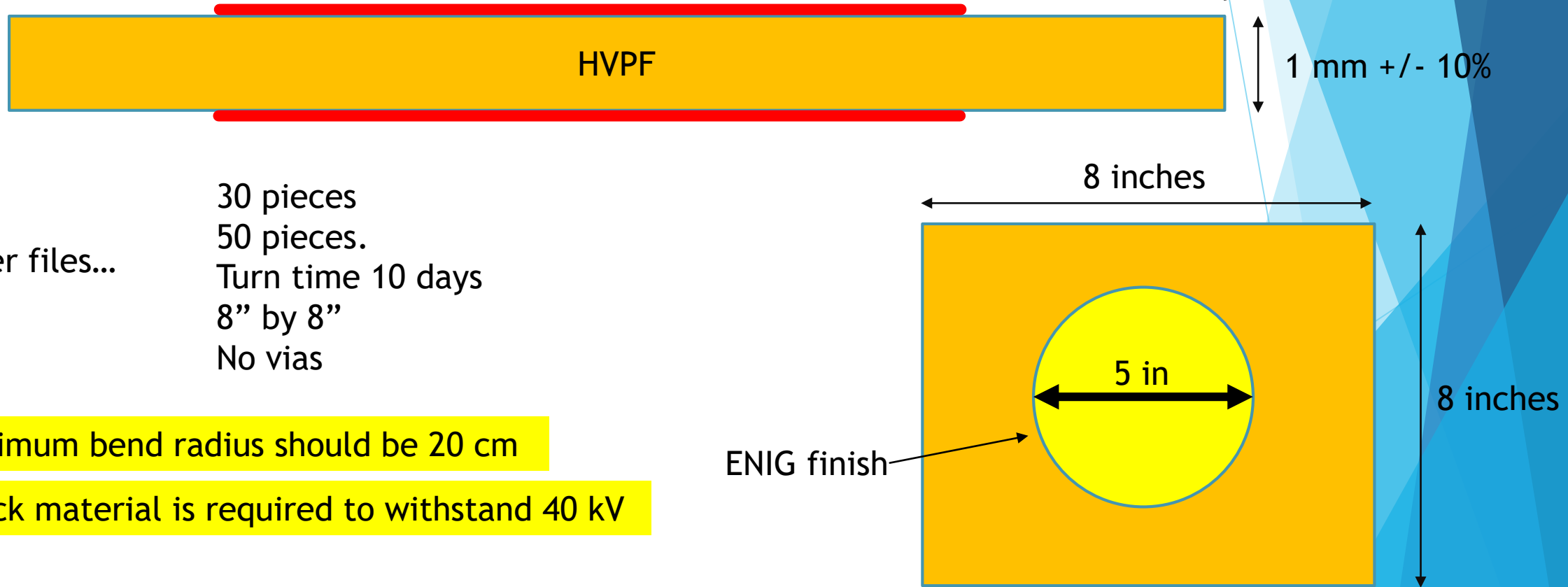
Minimum bend radius should be 20 cm

1mm thick material is required to withstand 40 kV

ENIG finish

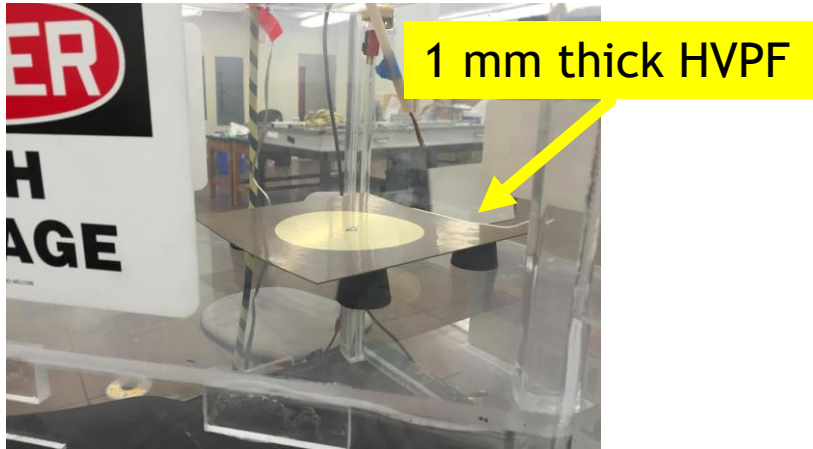
5 in

8 inches



HV Testing...

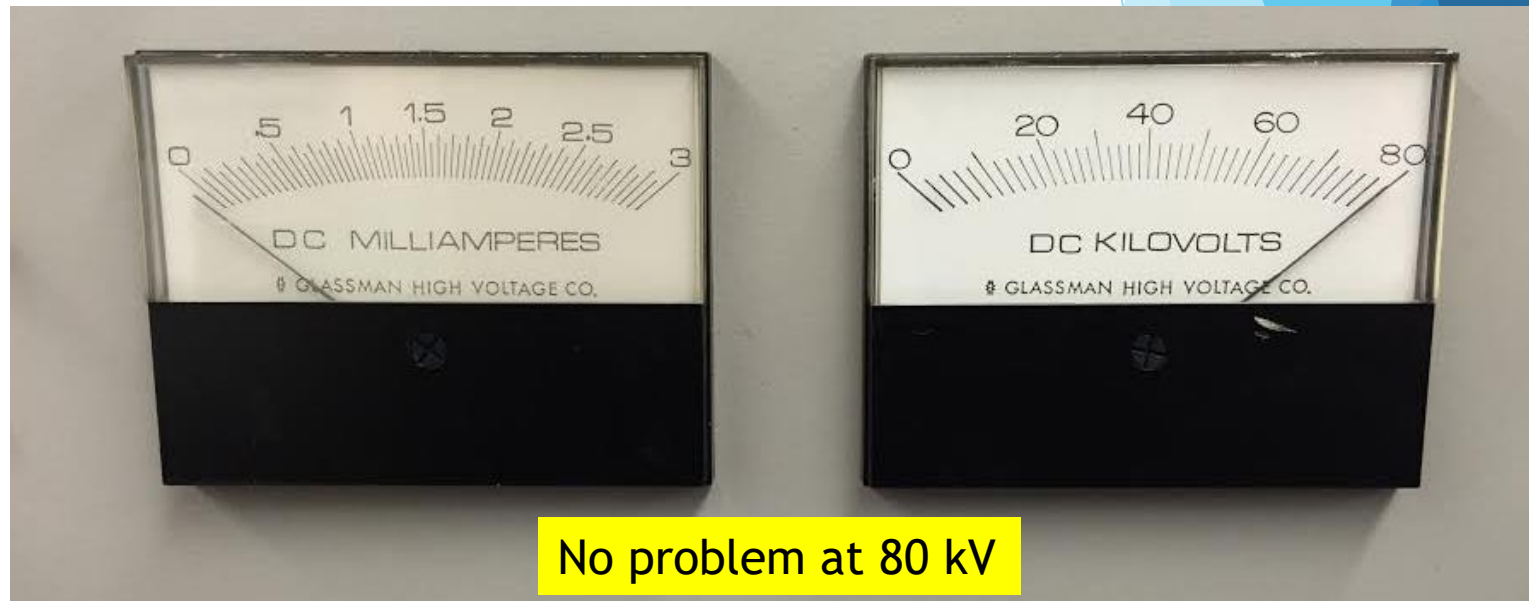
Reminder: Operates at 32 kV + GEM voltage, ~35 kV.



~65 kV sparks around edge, through air.

Add PVC pipe to lengthen air path...

- ▶ My next biggest HV power supply is 450 kV, but that one powers injector to SBU tandem accelerator.
- ▶ Rich Lefferts believes that when this one sparks through material, that (like the 20 kV, 40 kV, and 80 kV units) it will not hurt the power supply.
- ▶ Not our current priority...



No problem at 80 kV

Mandrel

Mandrel & Tooling similar to Lathe...

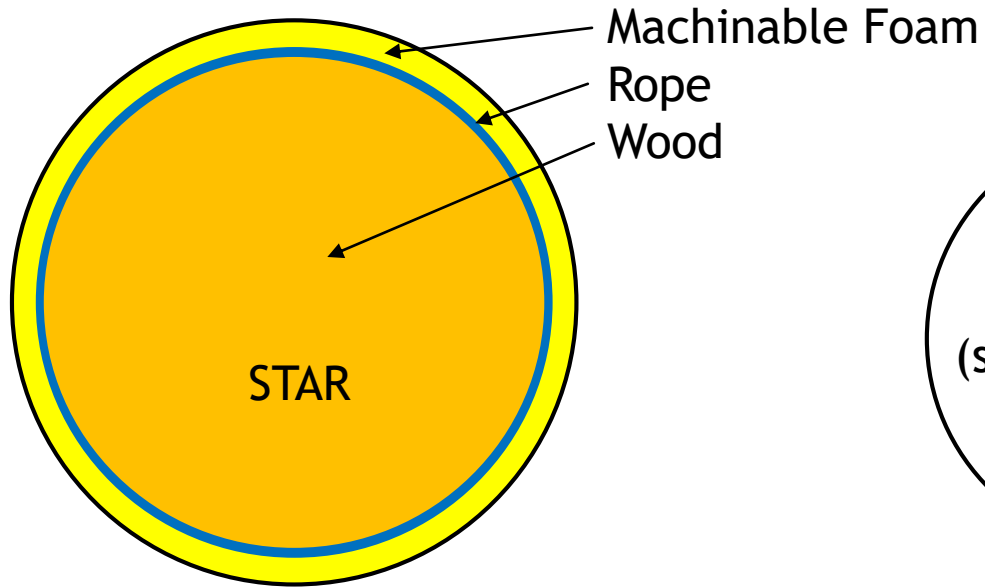


- ▶ Hexcell honeycomb sandwiches are familiar to many in planar form.
- ▶ To do the same in a cylinder, you need a “Mandrel”.
- ▶ Question: How do you get the damned thing off the mandrel?

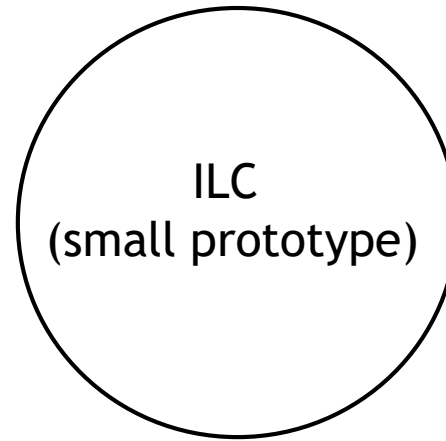


Field Cage Construction

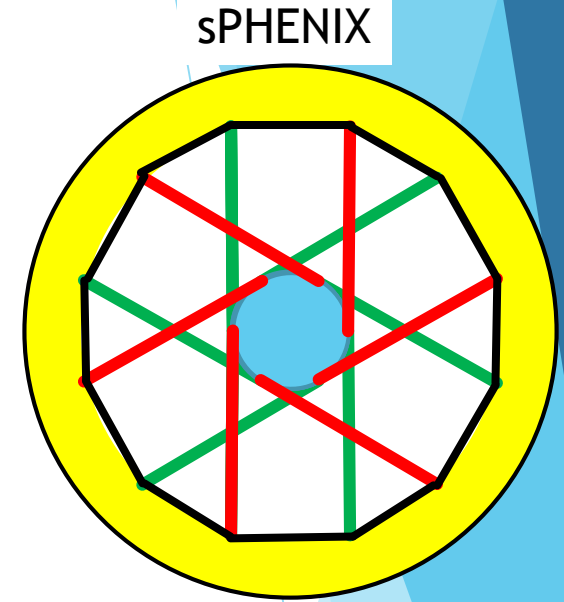
Niv Ramasubramanian: SBU physics grad student, BA in engineering.



- ▶ Wooden cylinder.
- ▶ Double layer of rope on cylinder.
- ▶ Machinable foam:
 - ▶ Turned (like a lathe) to correct outer radius.
- ▶ After layers glued...rope pulled from end to free the field cage.



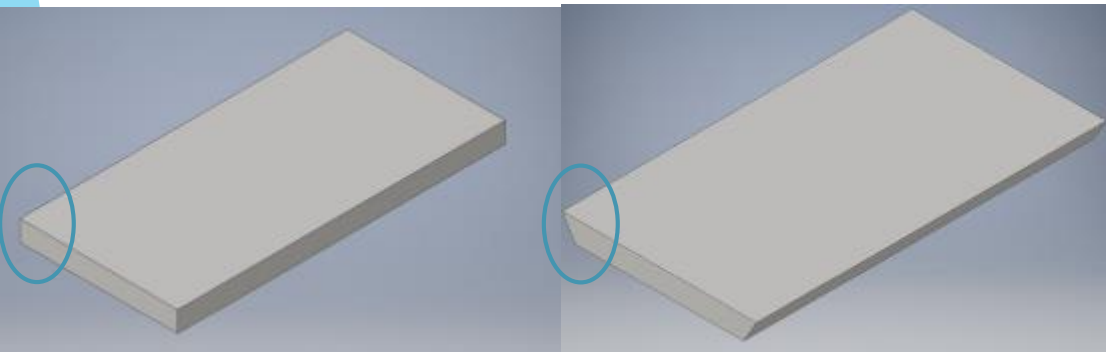
- ▶ Steel cylinder with internal mechanics.
- ▶ Internal mechanics allows the cylinder to retract from the field cage at the end.



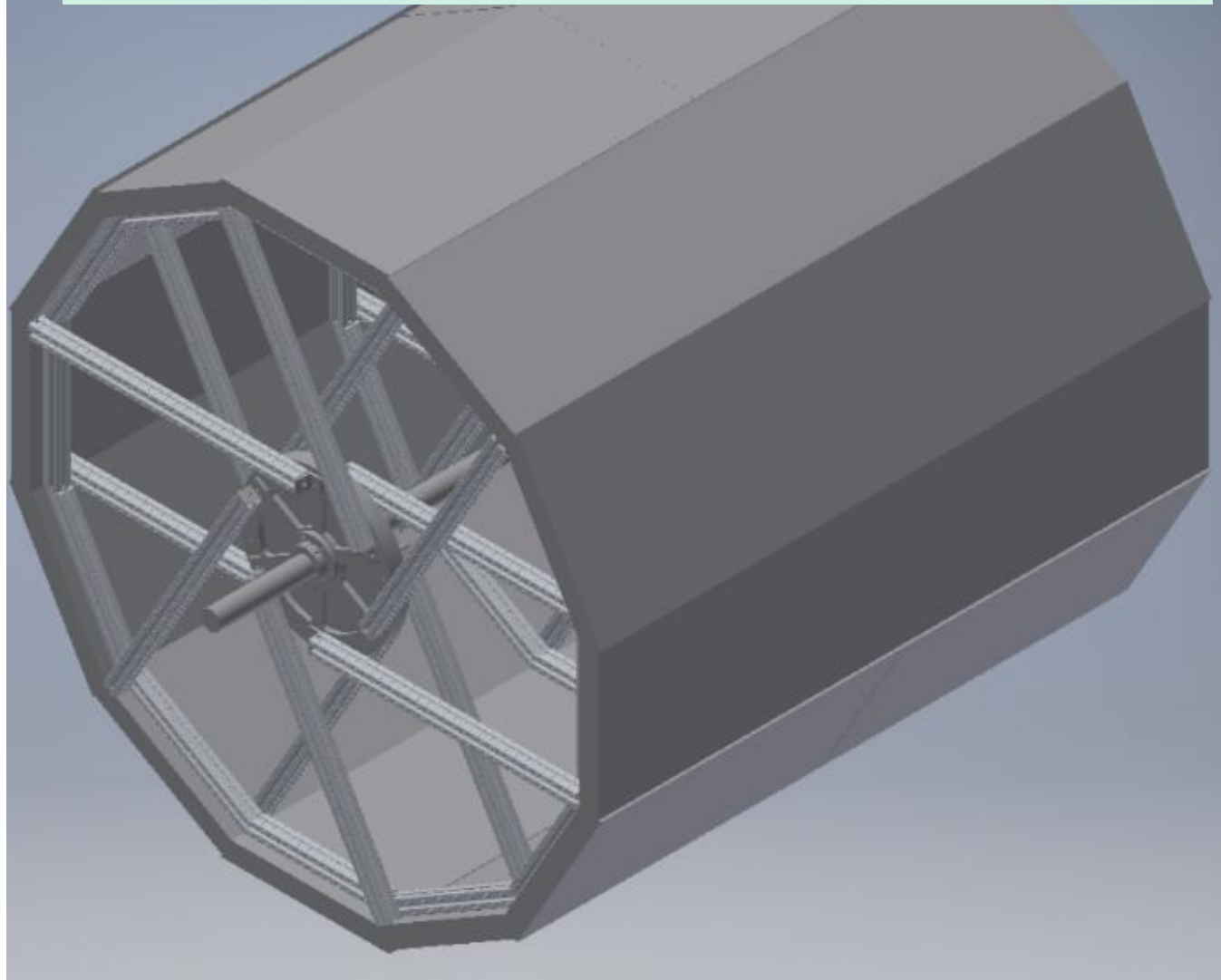
- ▶ Compromise between STAR and ILC
- ▶ The cylinder supporting the machinable foam is like a bicycle wheel (sturdy)
- ▶ 3 Wheels make a cylinder.
- ▶ Since $\frac{1}{2}$ length is only 80cm, we can reach in to disassemble 80-20 pieces freeing the field cage.

Mandrel CAD Design.

- ▶ Each wheel is held to the precision steel shaft via a collar.
- ▶ The collar is positioned by the SBU shop to be centered in the wheel.
- ▶ The foam blocks are held from the inside via screws (e.g. drywall screws).
- ▶ “Even” numbered blocks: square sides.
- ▶ “Odd” numbered blocks angled sides.
- ▶ Because of the asymmetry, there is a lip at every edge that will be removed.



Samples of 3 densities of foam in hand & “butterboard”
Currently favoring the highest density rohacell



Reminder: Basic concept is to turn (as in lathe) the rohacell foam into a precise cylinder to lay up the field cage walls.

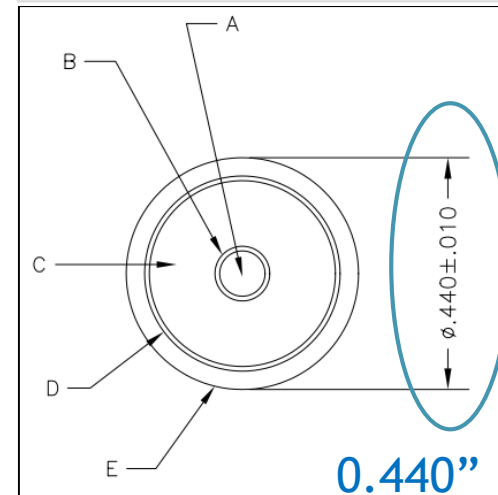
Measure Twice Cut once...

- ▶ We've settled on an outer radius of the device:
 - ▶ 80cm minus 2 cm "stay clear" zone → 78 cm outer radius.
- ▶ QUESTION: What is the exact thickness of the exterior shell?
 - ▶ Since the MANDREL RADIUS is set to the INNER RADIUS size, we should **calculate first** and **then cut metal**.
 - ▶ STAR field cage is 1cm (kapton-hexcell-kapton) and their gas enclosure is also 1cm (aluminum-aluminumhex-aluminum).
 - ▶ Our current design specifies ½" honeycomb.
 - ▶ Set by HV cable diameter... should be driven by mechanical stability.
 - ▶ Sturdier than STAR.
 - ▶ Want to know more before cutting metal...

Dielectric Sciences, Inc.
A High Voltage Technology Group Company

Specifications

Voltage	30 KVAC 100 KVDC
Cable Type	1-Conductor Cable
No. of Conductors	1
Diameter	0.440 in
Gauge	16 AWG
Conductor Material	Tin-plated Copper
Shield	Tin-coated Copper Braid
Insulation Material	Polyethylene
Jacket Material	PVC



LEGEND

- A. #16 AWG (19/29) T.C.
- B. SEMICON POLYETHYLENE TO $\phi.100$
- C. INSULATING POLYETHYLENE TO $\phi.360 \pm .010$
- D. BRAIDED SHIELD, #34 AWG T.C. , 90% COV
9 ENDS, 24 CARRIER
- E. JACKET: PVC: BLACK

NOTES:

- 1. TEST VOLTAGE: 110KVDC- 10 MINUTES
- 2. JACKET SPARK TEST: 5KV

QUESTION: How do you simulate Mechanics of Honeycomb materials in CAD?

Figure of Merit Comparisons:

A	B	C	D	E	F	G	H	I	J	K
Detector	Mass of beam (kg)	l (m)	h(m) t of HC	l^3	h^2	Effective ET	$(l^3)/(h^2 \cdot ET)$	relative pressure "deflection"	$(M \cdot l^3)/(h^2 \cdot ET)$	relative gravity "deflection"
ALICE		5.1	0.03	132.651	0.0009		#REF!			
ILC	1.43	4.3	0.02394	79.507	0.0005731236	1.906	72783.70819	1.73435361	104080.7027	7.230687064
STAR - field cage	1.4	4.2	0.00967	74.088	0.0000935089	0.85875	922631.2769	21.98526189	1291683.788	89.73576283
STAR - containment vessel	4.6	4.2	0.008	74.088	0.000064	13.8	83885.86957	1.998905584	385875	26.80748014
SPHENIX	0.343	1.6	0.01305	4.096	0.0001703025	0.5731158	41965.89885	1	14394.30331	1

Detector	relative pressure "deflection"	relative gravity "deflection"
ALICE		
ILC	1.73435361	7.230687064
STAR - field cage	21.98526189	89.73576283
STAR - containment vessel	1.998905584	26.80748014
SPHENIX	1	1

- ▶ Since STAR field cage does not hold pressure this is an inappropriate comparison.
- ▶ By simple scaling laws, sPHENIX field cage deflection is significantly smaller under pressure and gravity than the larger TPCs.
- ▶ Therefore we conclude that the ½" specification for the honeycomb is correct:
 - ▶ Pressure/Gravity sag is fine and would tolerate thinner honeycomb.
 - ▶ Desire to bury HV cable inside a "slot" in the honeycomb likes current size.
- ▶ Ready to proceed with the mandrel manufacture ("measured twice").

SBU Machine Shop making all the Parts...



Walter



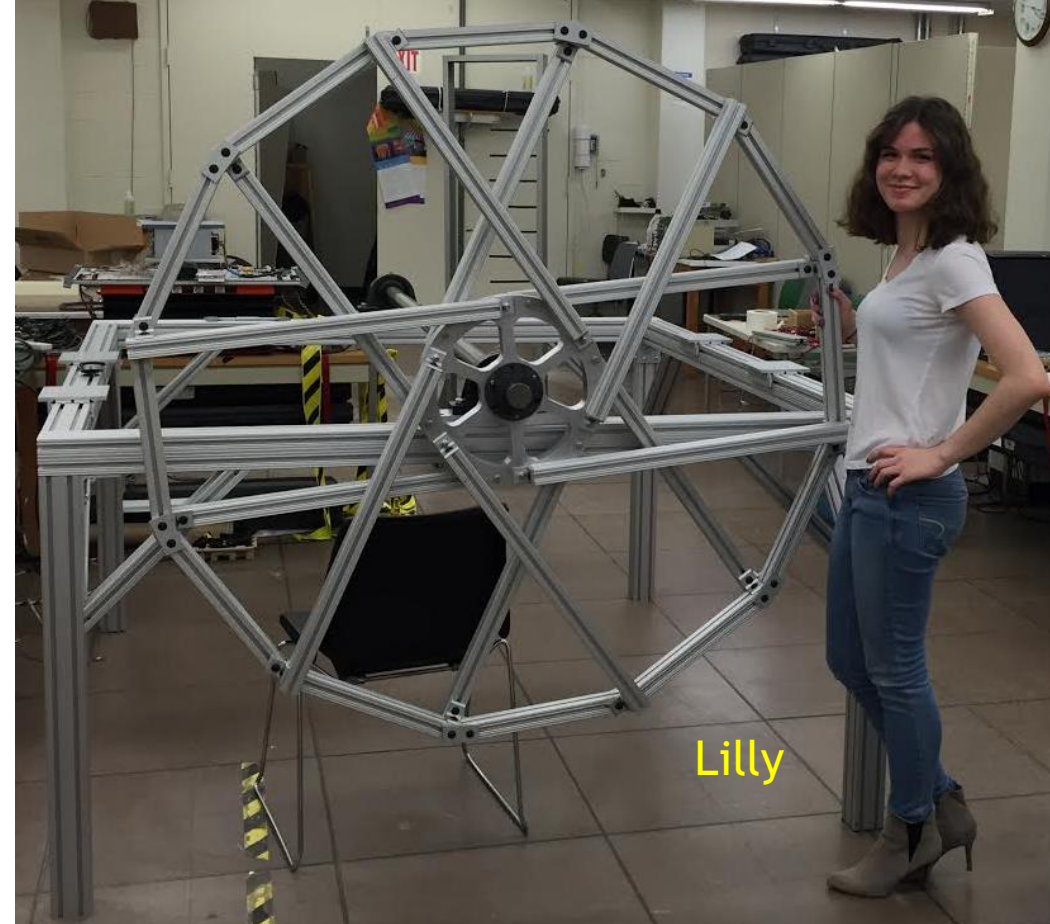
Jeff



Saving Money:
Holes by bandsaw then mill....



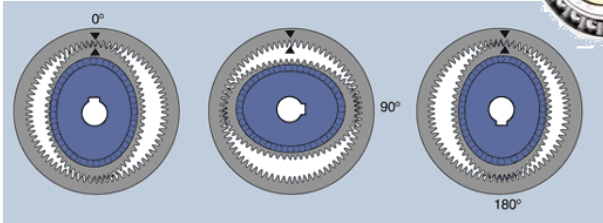
Final Polish



Lilly

- ▶ Parts for the three wheels are done.
- ▶ [Click Me](#)

Progress...



LM13 magnetic ring encoder system

- Resolutions from 1,280 to 327,680 counts per revolution
- High speed operation to 20,000 revolutions per minute
- Excellent dirt immunity



RKF

The RKF series is compact and includes high torque AC servo actuators with high rotational accuracy, a flange output combining one of our Harmonic Drive® gears and an AC servo motor. The RKF Series is designed to operate with a wide range of third party drivers as well as Harmonic Drive LLC's RTL Series, and REL Series.



Accelnet Plus 1-Axis Panel



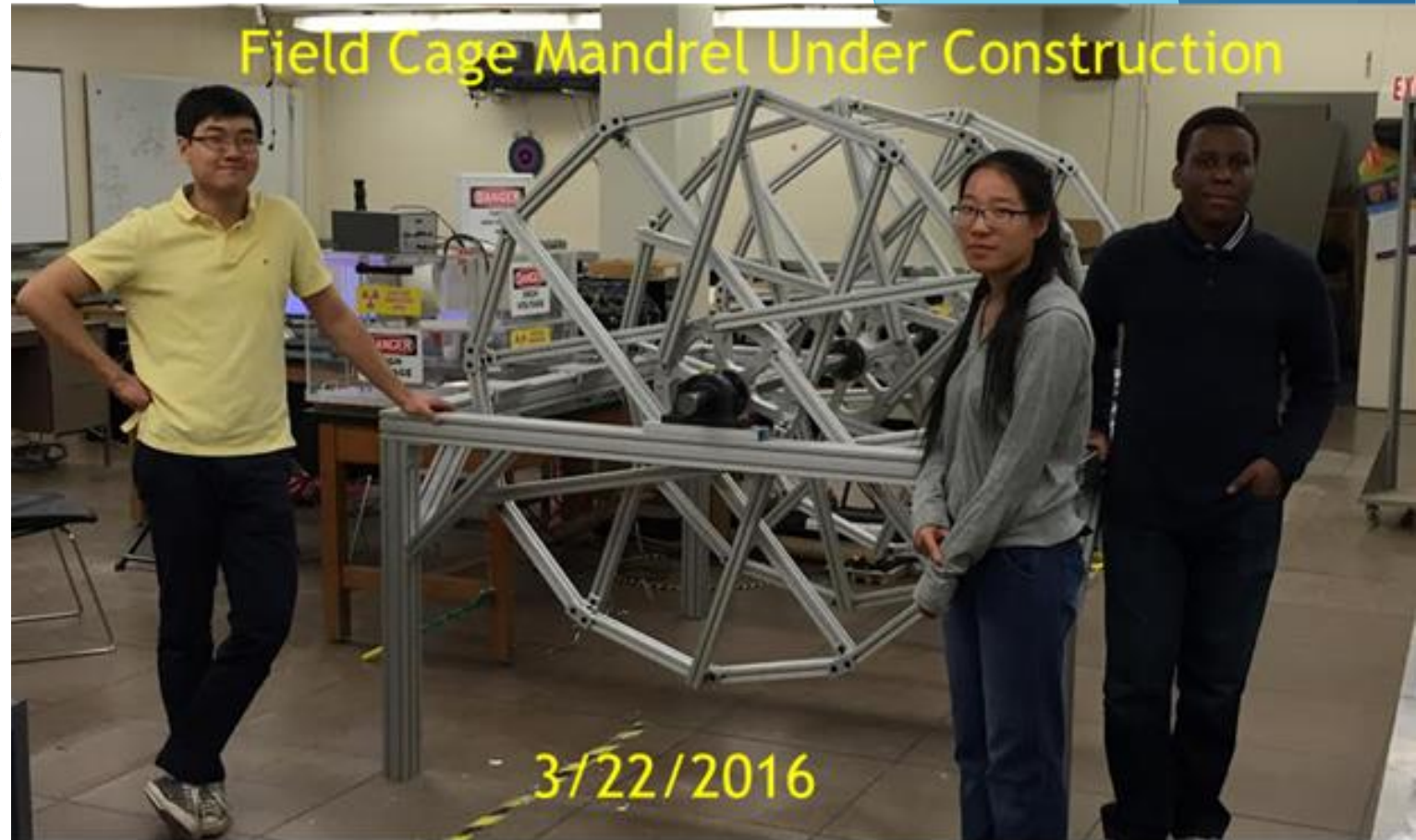
RSF-Mini

These brushless servo actuators utilize zero backlash Harmonic Drive® precision gears for precise motion control. The RSF Mini Series is designed to operate with a wide range of third party drivers as well as Harmonic Drive LLC's DC Series, DDP Series, DEP Series, and HA660 drivers.

LA11 absolute magnetic encoder system

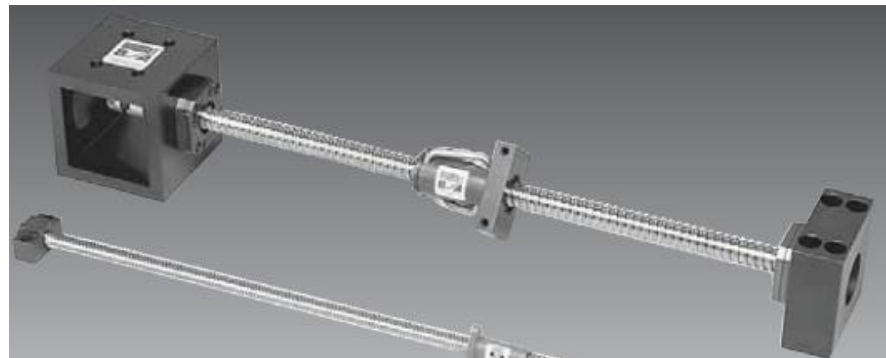
- True absolute system
- High accuracy
- Resolutions up to 0.244 μm
- Axis lengths up to 16.3 m
- Speeds up to 7 m/s at 0.977 μm resolution

Field Cage Mandrel Under Construction



Using all Harmonic Drive Motors:

- Zero Backlash.
- Internal geardown.
- 30% teeth engaged.
- High torque at very low RPM
- Linear position measured to 0.25 μm .
- $r\phi$ position 100 μm at outer edge.



Field Stripes

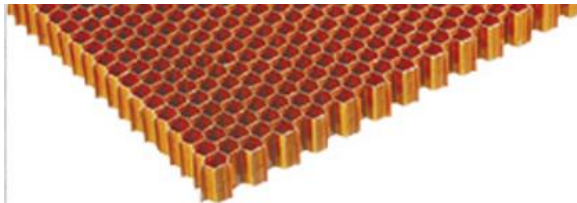
Known:

- ▶ Layering of materials:
striped kapton, insulating kapton, FR4-Cu, hexcell, Cu-FR4-Cu
- ▶ Striped kapton:
All-Flex...18" x 16' (yup, feet) = \$3000 each.
 $1.6\text{m}/18" = 3.5$; use 5 pieces (I do *NOT* want a seam in the middle).
- ▶ Insulating Kapton:

Pyralux® AP Copper-Clad Laminate

• Available in polyimide thicknesses of 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, and 6.0 mils; 7.0-20 mils available upon special re

- ▶ Lead carrying HV:
- ▶ Hexcell 4'x8' from Plascore



PN2 Aerospace Grade Aramid Fiber Honeycomb

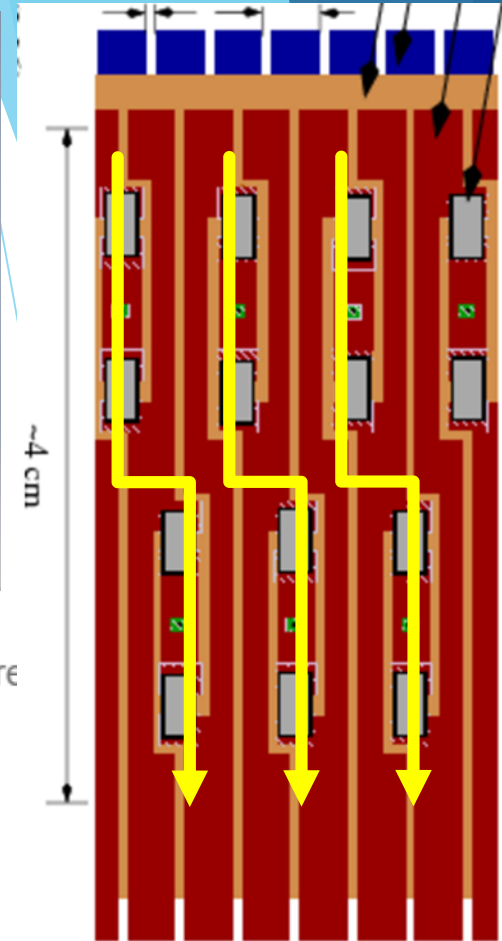
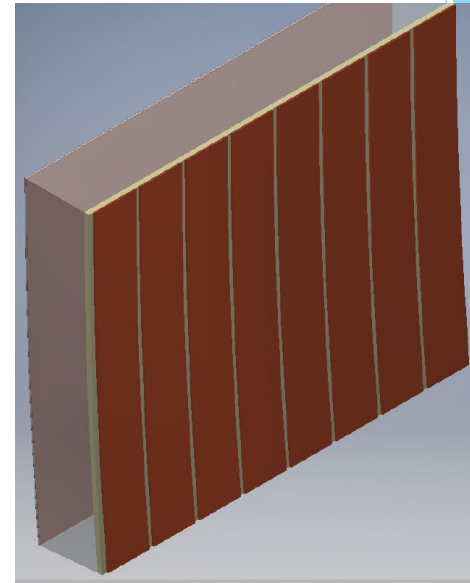
Dielectric Sciences, Inc. A High Voltage Technology Group Company	
Specifications	
Voltage	30 KVAC 100 KVDC
Cable Type	1-Conductor Cable
No. of Conductors	1
Diameter	0.440 in
Gauge	16 AWG
Conductor Material	Tin-plated Copper
Shield	Tin-coated Copper Braid
Insulation Material	Polyethylene
Jacket Material	PVC

LEGEND

A. #16 AWG (19/29) T.C.
B. SEMICON POLYETHYLENE TO $\phi.100$
C. INSULATING POLYETHYLENE TO $\phi.360 \pm .010$
D. BRAIDED SHIELD, #34 AWG T.C., 90% COV
9 ENDS, 24 CARRIER
E. JACKET: PVC: BLACK

NOTES:

1. TEST VOLTAGE: 110KVDC- 10 MINUTES
2. JACKET SPARK TEST: 5KV



ILC Resistor Chain

Aligning Stripes onto Mandrel:
Learn by doing...

Tiling the stripes.

- ▶ All-Flex has unique capability to make VERY long kapton circuits (up to 40 feet).
- ▶ The width is material limited (17.7" fiducial).
- ▶ 3.5 "tiles" along TPC length.
- ▶ Real life:
 - ▶ I *DO NOT* want a seam in the middle.
 - ▶ Therefore we will have 5 tiles (order 8).

March 11, 2016

Stony Brook University
Tom Hemmick
3060 Little Neck Rd.
Cutchogue, NY 11935
Phone – 516-982-1403
Email - tkhemmick@gmail.com

Subject: Quotation for P/N(s): **MAXI FLEX**
Reference Number: **STONY BROOK Q160395DSMX REV1**

Dear Tom,

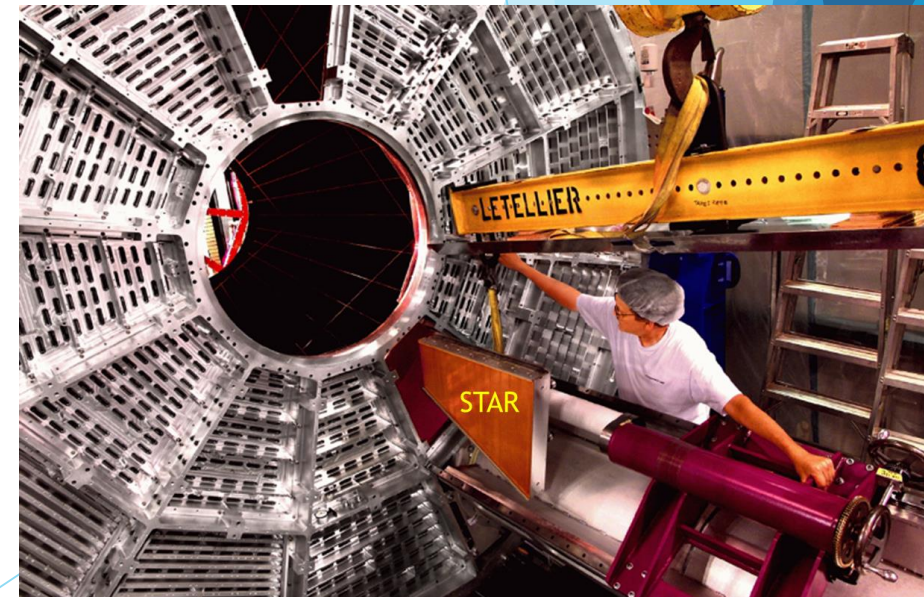
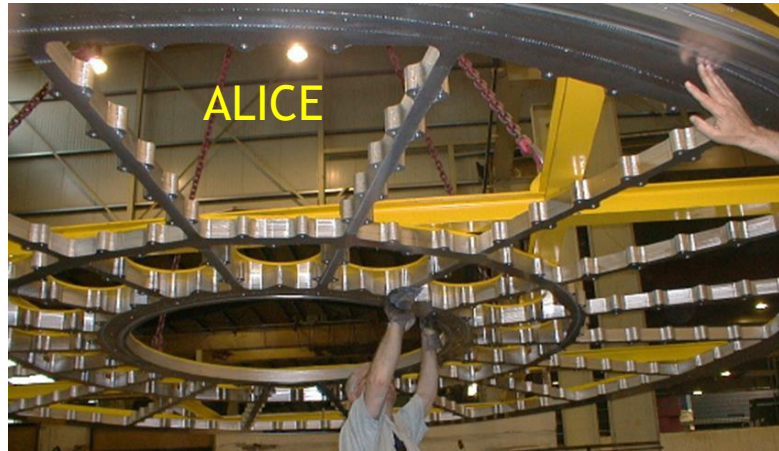
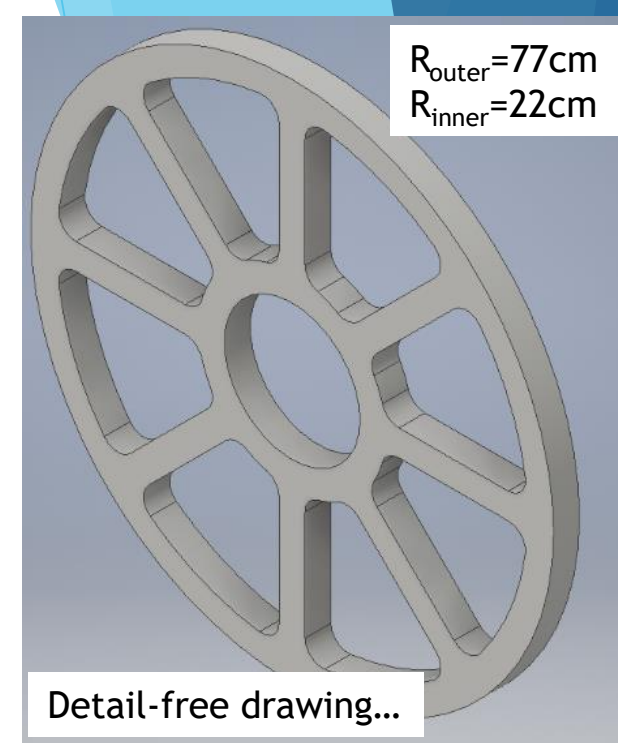
Thank you for the opportunity to bid on your flexible circuit requirement. We are pleased to submit the following budgetary quotation for your review:

Order Quantity	Price
Tooling and NRE	\$1,200.00
4 units	\$3,500.00/unit
8 units	\$2,925.00/unit

Statement of Work:

End Cap Design

- ▶ The End Cap design requires significantly more work!
- ▶ This is the “interface” to the rest of sPHENIX and must be designed collaboratively with BNL engineering.
 - ▶ Flatness critical for field shaping.
 - ▶ Low deflection required.
- ▶ Nonetheless, we should spend some time on the conceptual foundation of what we want:
 - ▶ STAR/ALICE = MASSIVE WHEELS.
 - ▶ Followed by flux return (STAR) or muon measurement (ALICE).
 - ▶ ILC follows the end caps with additional detector layers.
 - ▶ Must be thin to make good measurements behind it.



ILD @ ILC

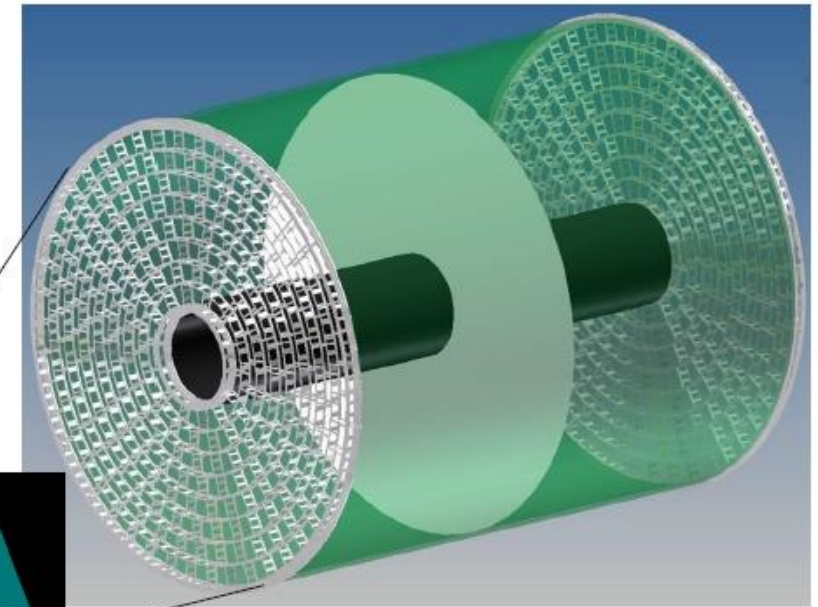
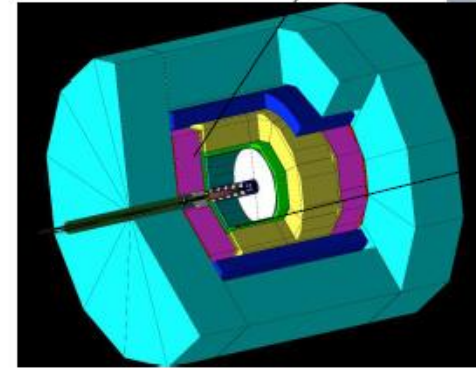
- ▶ STAR-like diameter
- ▶ ALICE-like length
- ▶ Goal: $\sigma \sim 100\text{-}150\text{ }\mu\text{m}$
- ▶ Test: $\sigma = 120\text{ }\mu\text{m}$



Work at Cornell: development of the endplate and module mechanical structure to satisfy the material and rigidity requirements of the ILD.

The ILD TPC has dimensions:

outer radius 1808 mm
inner radius 329 mm
half length 2350 mm



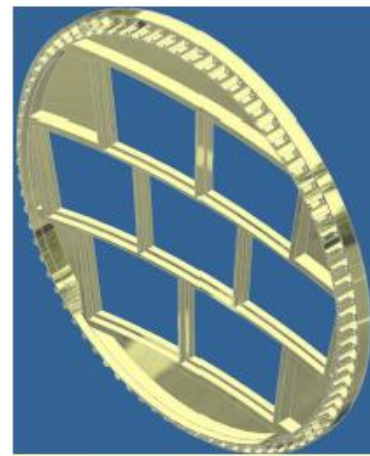
- Prototype tests during development of the ILD TPC endplate design
- ILD TPC endplate design, analysis
- LP2 endplate construction and testing as a validation of the ILD design
- Further measurements on the LP2 endplate
- Further analysis on the ILD endplate design
- Comments on viability of constructing the ILD endplate

Evolution

- ▶ Two are thin enough:
 - ▶ Hybrid
 - ▶ Space Frame
- ▶ ILD finds that the Hybrid is not rigid enough under pressure.
- ▶ Our small size could result in a different solution.



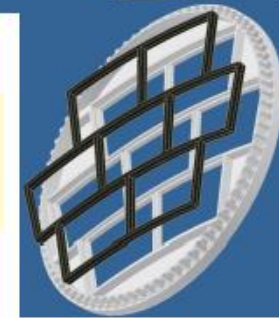
LP1 endplate,
thick aluminum



lightened, all aluminum



aluminum/
carbon fiber
hybrid



space frame

Various technologies were considered for the ILD endplate
(illustrated here for an LP1-size endplate).

The LP1 endplate structure is rejected because of high material.

Various **lighted endplates** illustrated contributions to the endplate strength.

Low material **hybrid construction** was considered in an effort
to provide the strength of the LP1 design, with significantly reduced material.
But, there is insufficient rigidity when scaled to the size of the ILD.

Only a **space-frame** promises to provide the required strength-to-material.

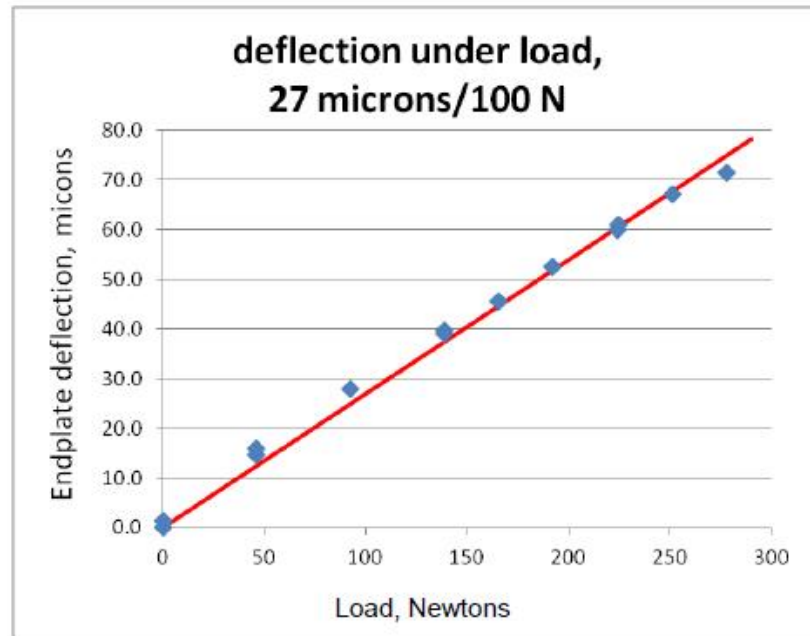
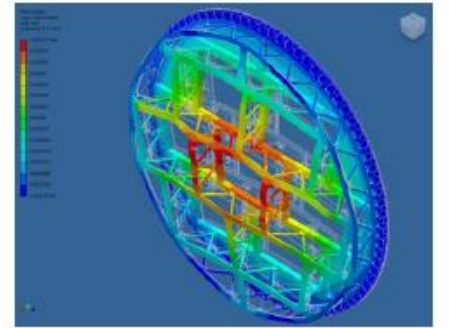
Tough Beans...

- ▶ Real life is always tougher than simulation...
- ▶ Still not bad at all.
- ▶ ILD is headed toward space frame, but it is not clear that this is the right choice for us...

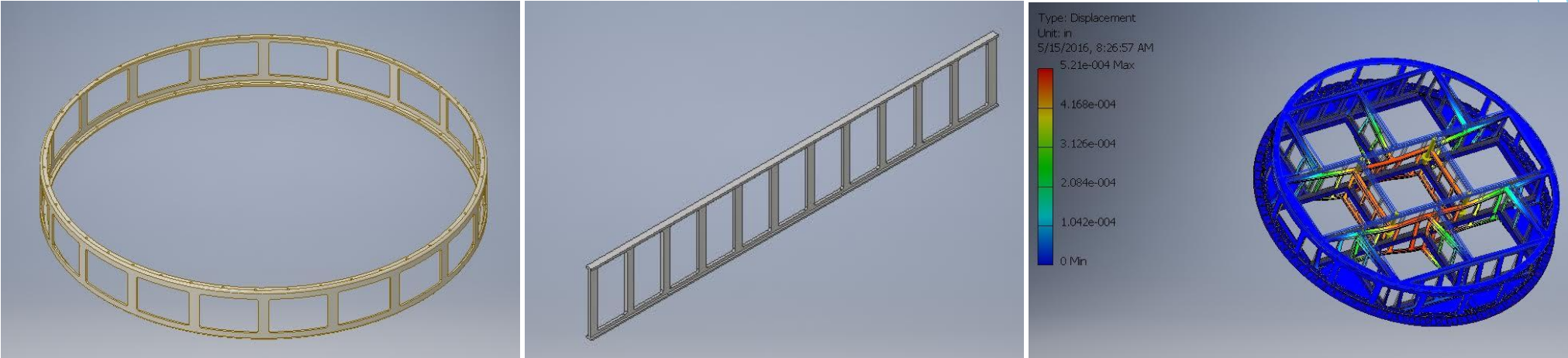
Validation of the FEA with 0.8 meter diameter LP2 endplate

The FEA predicts a longitudinal deflection of 23 microns / 100 N load.
(with the load applied at the center module.)

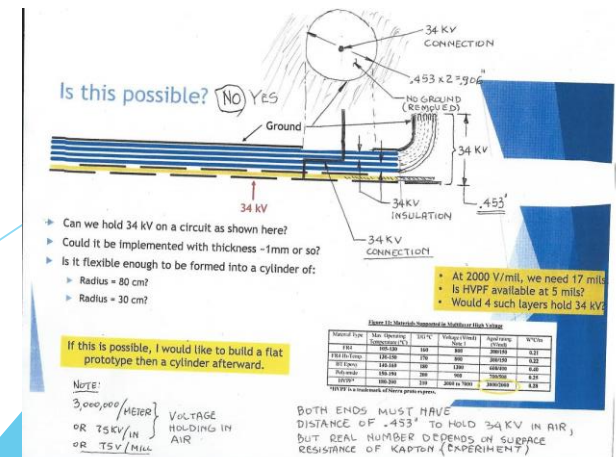
Measured deflection is 27 microns/100 N load **17% higher.**



measuring the deflection



- ## Initial work on feedthrough



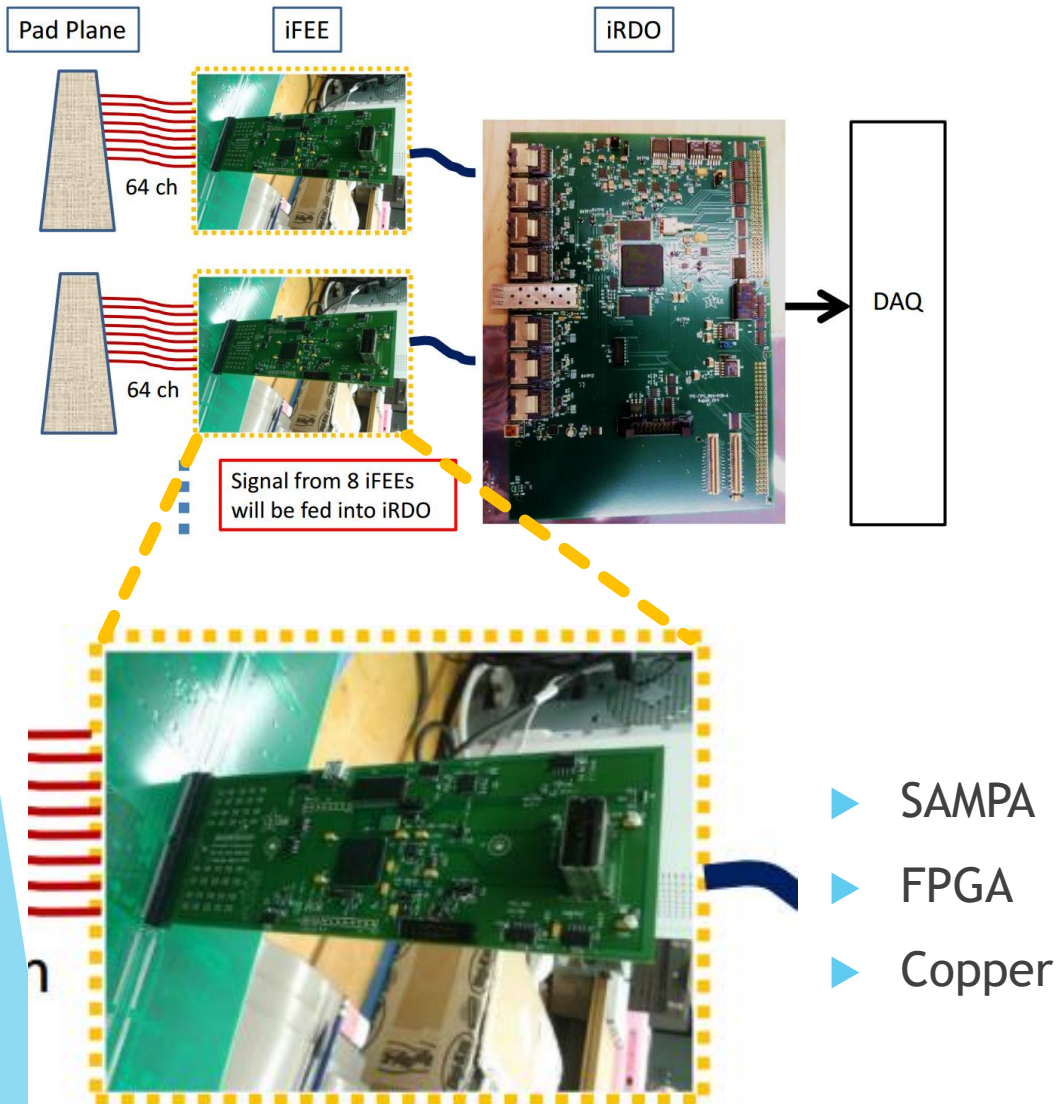
Cool new Development:



- ▶ ILC TPC Prototype will be given to us for experiments.
- ▶ This comes with 10,000 channels of proper-polarity electronics!
- ▶ QUESTION: Could we put this (and later the real TPC Field Cage Prototype) @ RHIC?
- ▶ FANTASTIC opportunity for engineering runs (w/o B-field) during the BES!
- ▶ Helps alleviate concern over “start-up woes”.

Electronics

STAR iTPC Upgrade



sPHENIX TPC electronics meeting

Friday, May 13, 2016 from **10:00** to **12:00** (US/Eastern)
at **Universe (2-160)**

outside experts: Tonko Ljubicic, Bob Sheetz

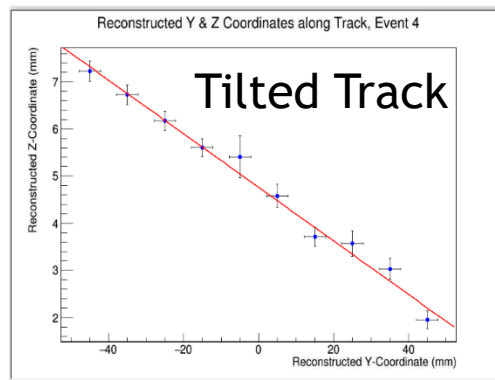
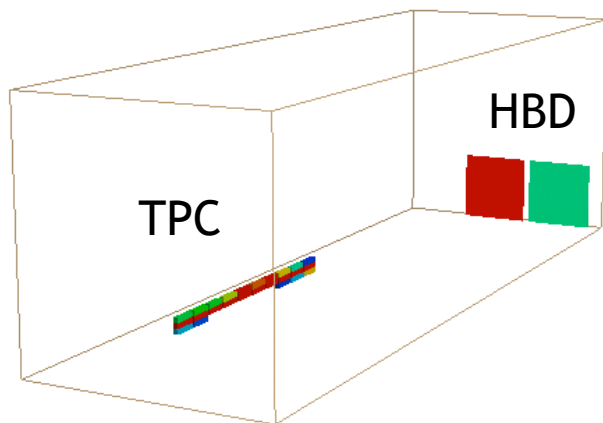


The correct design for sPHENIX is clear:

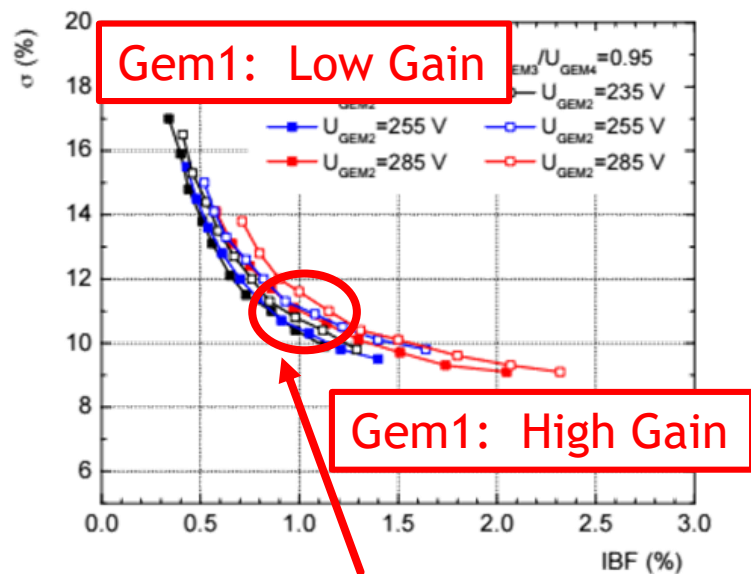
- SAMPA
- FPGA
- Optical
- Commercial/Home-Brew into PC.

Many more details...but not for today.

- ▶ Code slow but running.
- ▶ Reasonable interface for measuring IBF now ready.
- ▶ Calculations and reasonable extrapolation show that our IBF problem will be much smaller than that faced by STAR/ALICE.
- ▶ There is more to do in reducing IBF (possibly very significantly).
- ▶ Likely “normal” considerations will become limit to TPC performance.
- ▶ TONS of interesting work to do:
 - ▶ Design, construction, simulation, IBF, test beam, ...
 - ▶ Already a large crew but we can use many more.



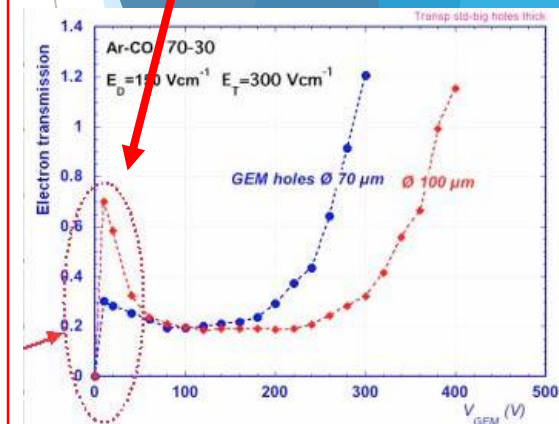
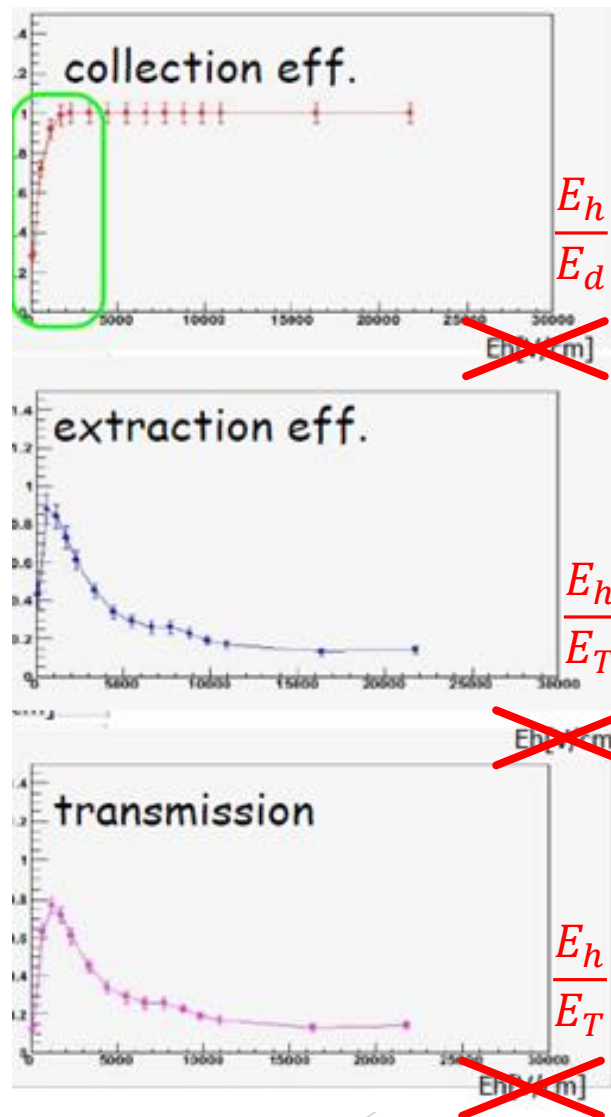
Basic Parameter Limits:



ALICE Operating Point

- ▶ 2-GEM plus μ MEGA a bit better but the compromise between GEM-1 gain and resolution persists.
- ▶ New(?) thought...
 - ▶ Can we get IBF protection w/ GAIN=1.
 - ▶ ILC uses this for a “GEM-based gating grid”.
 - ▶ moderate E_T but modify holes to achieve good operation.

ILC calculations of the so-called “Sauli point”



- ILC folks make plot with fixed E_d and E_T .
- E_d going down and E_T going up are the RIGHT DIRECTION for achieving low IBF.

MPGD Gain Stage

NOTE: Unavoidable feedback 1st GEM

- ▶ Electron/Ion drift differences “enhanced” by staggered drift field options.
- ▶ Leads to four layers of GEM.
- ▶ Other considerations:
 - ▶ Hole pattern rotation.
 - ▶ Hole spacing changes.

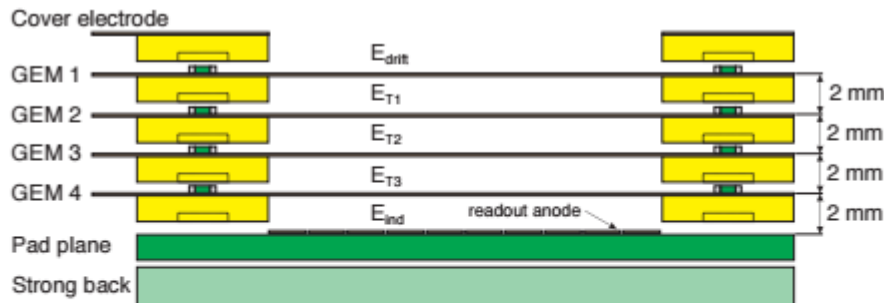
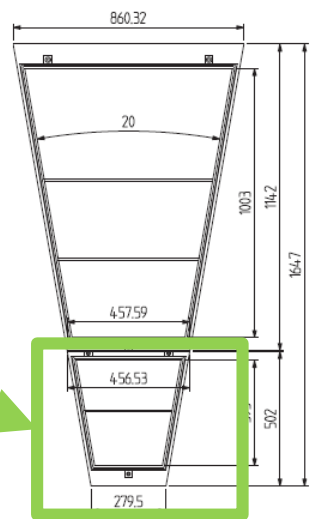


Figure 4.6: Schematic exploded cross section of the GEM stack. Each GEM foil is glued onto a 2 mm thick support frame defining the gap. The designations of the GEM foils and electric fields used in this TDR are also given. E_{drift} corresponds to the drift field, E_{Tj} denote the transfer fields between GEM foils, and E_{ind} the induction field between the fourth GEM and the pad plane. The readout anode (see Eq. (4.2)) is indicated as well. The drift cathode is defined by the drift electrode not shown on this schematic.

ALICE-USA builds this; roughly the same as our scale!



40 cm

Figure 4.4 shows an exploded view of a GEM IROC. It consists of the following components:



Figure 3.5: Left: Optical transparency of two standard GEM foils. Right: Illustration of the interference pattern that occurs when the foils are slightly rotated.



Figure 3.6: Left: Optical transparency of two standard GEM foils after rotation of one foil by 90°. Right: Illustration of the randomization of the relative hole positions.

Moire

Uniform

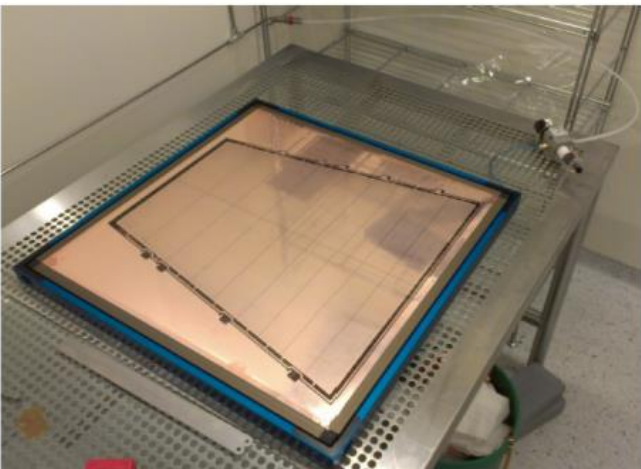


Figure 4.7: Photograph of an IROC GEM foil in the stretching frame.

Gas Choice - Wide Parameter Space...

Drift Velocity:

- Faster = Fewer Stacked evts
- Slower = Better 2-particle resolution.
- Plateau is highly desirable.

Longitudinal Diffusion (smaller is better):

- Influences 2-particle resolution.
- Determines p_z resolution.

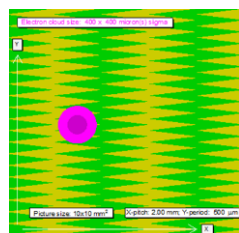
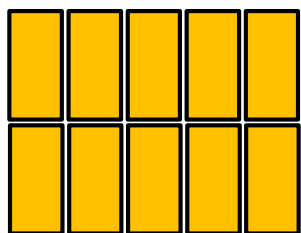
Transverse Diffusion:

- Influences single point precision.
- Spreads charge over sensors.
(coupled with pad geometry)

Field Uniformity:

- Electric Field for main drift
- Magnetic Field for main drift.

Space Charge

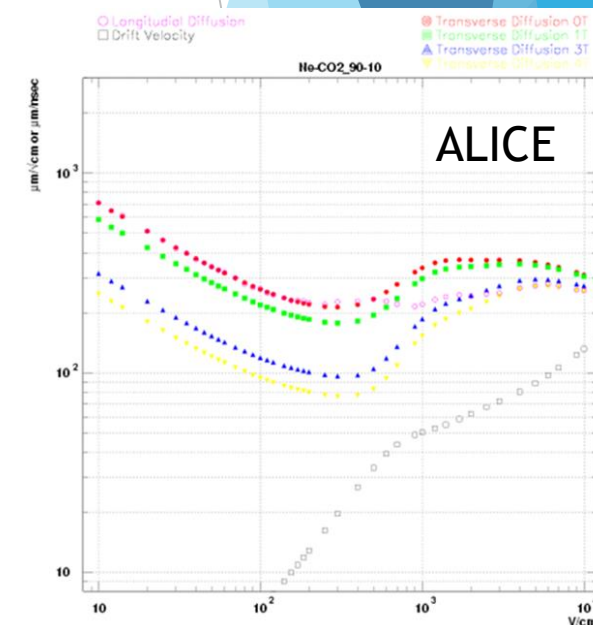
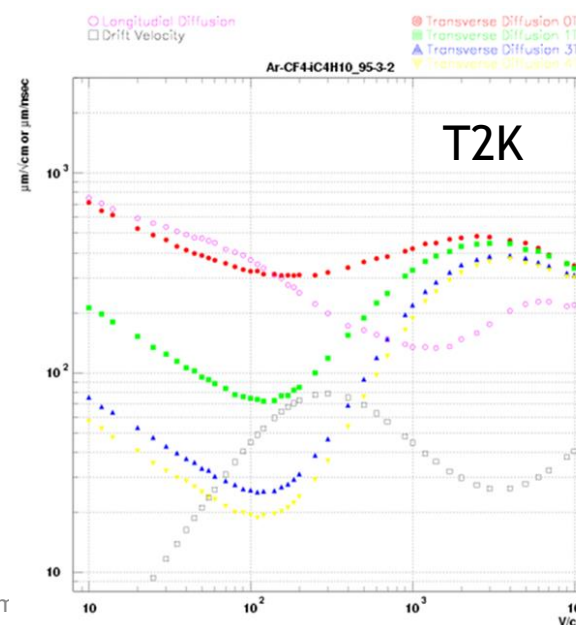


Minimum diffusion
~pad size

Minimum diffusion
~feature size

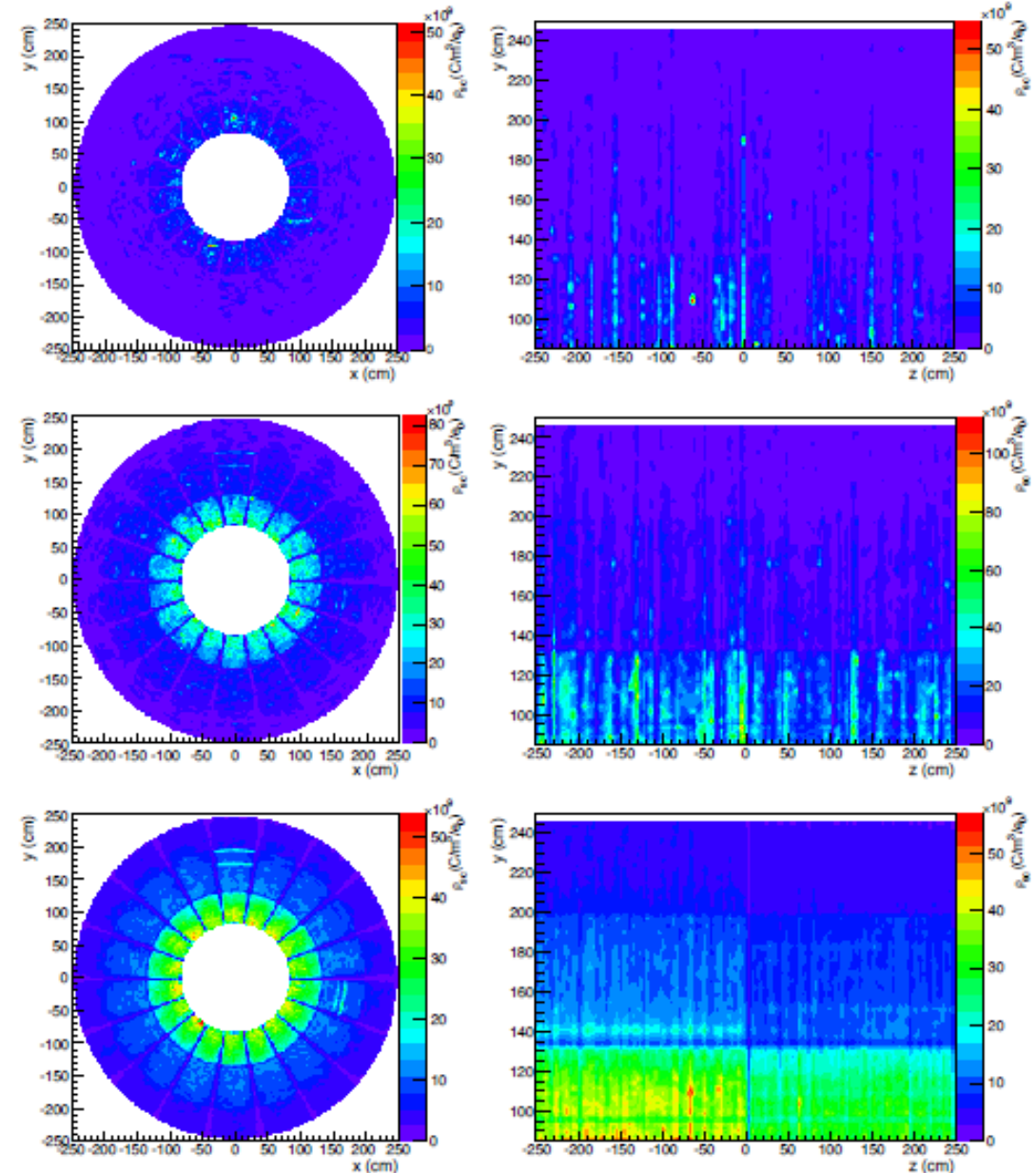
- ▶ By “Traditional” Considerations T2K is better.
- ▶ High rate/multiplicity Space Charge dominates.

Tracking System



Two Sources of Positive Ions

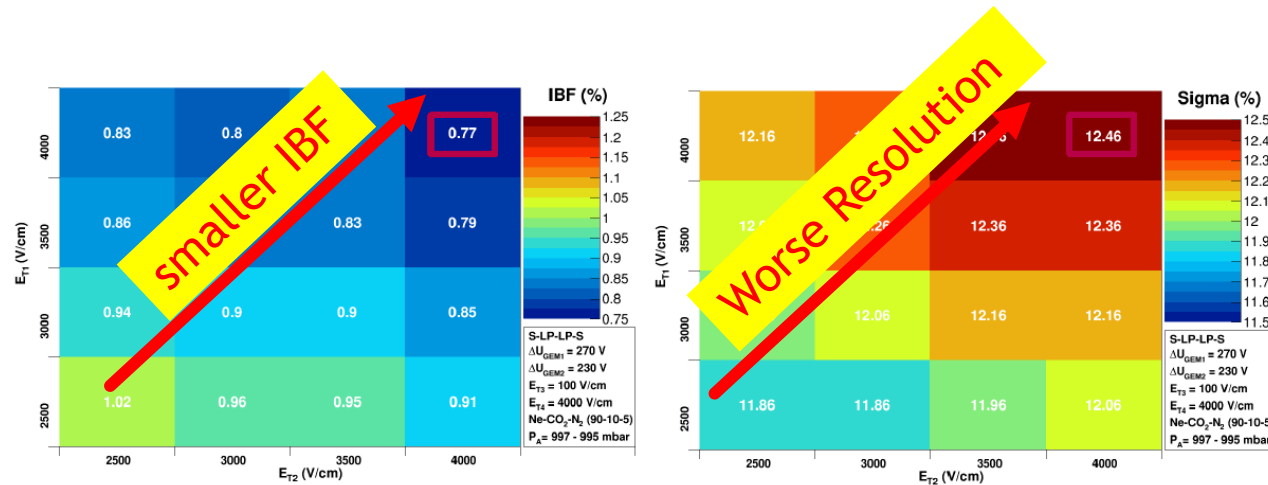
- ▶ In a gated TPC, the principle source of positive ions is primary ionization.
- ▶ Currently this is a larger effect in STAR than ALICE due to the differences in ion mobility and drift field strength.
- ▶ The un-gated TPC has consequences:
 - ▶ “Ion Back Flow” from the avalanche stage becomes the dominant contributor to the space charge.
 - ▶ The charge is rather “uneven” due to:
 - ▶ Pancakes of IBF from the avalanche stage.
 - ▶ Variations in gain.
 - ▶ Purposeful: inner sector high gain/gaps in azimuth.
 - ▶ Accidental: gain variations with time, temp, pressure...
- ▶ Significant R&D has been applied to find a “working point” suitable for the ALICE upgrade.



Recent results from ALICE easy to understand:

$E_{T1} - E_{T2}$ scan

$E_{T4} = 4000 \text{ V/cm}$

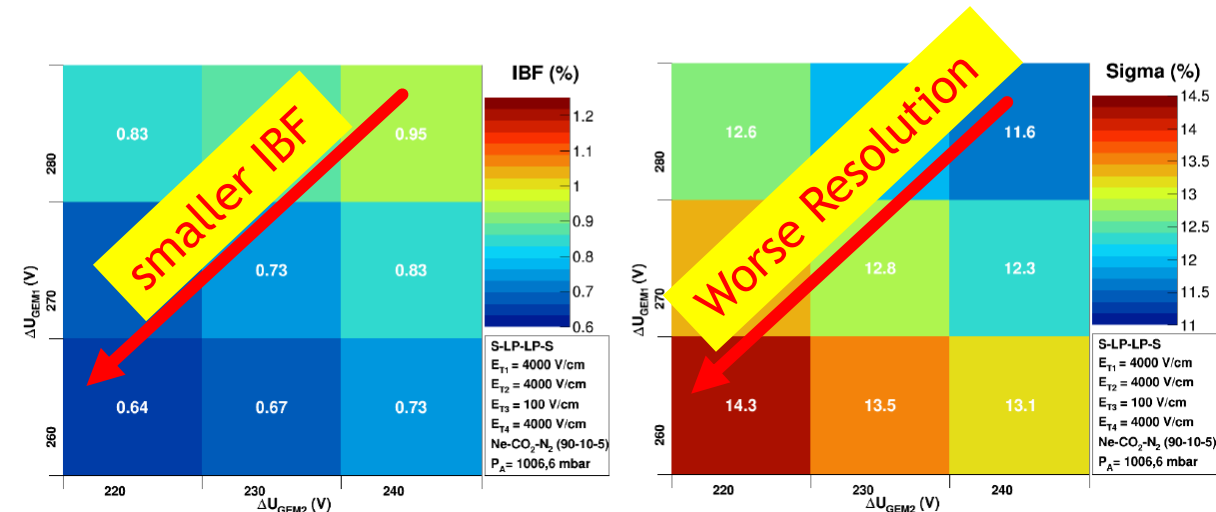


- ▶ Larger transfer fields more effectively couple the charge from the hole into the transfer gap.
- ▶ There is actually a plateau beyond which charge is forced into the top of the next GEM (known from HBD)
- ▶ This raises the “effective gain” with only small change to the “physical gain”.
- ▶ You then lower the physical gain and lower the IBF.

$U_{GEM1} - U_{GEM2}$ scan

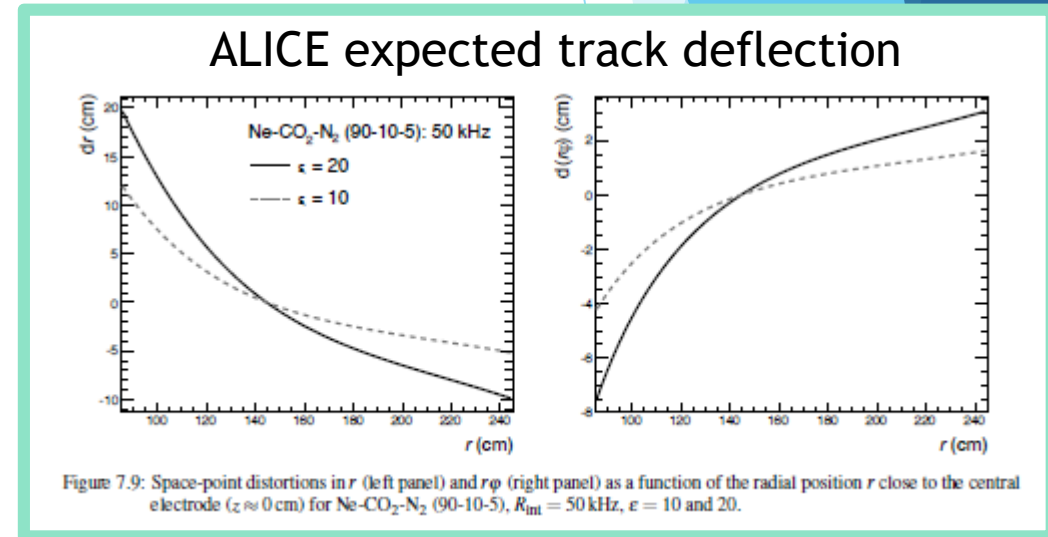
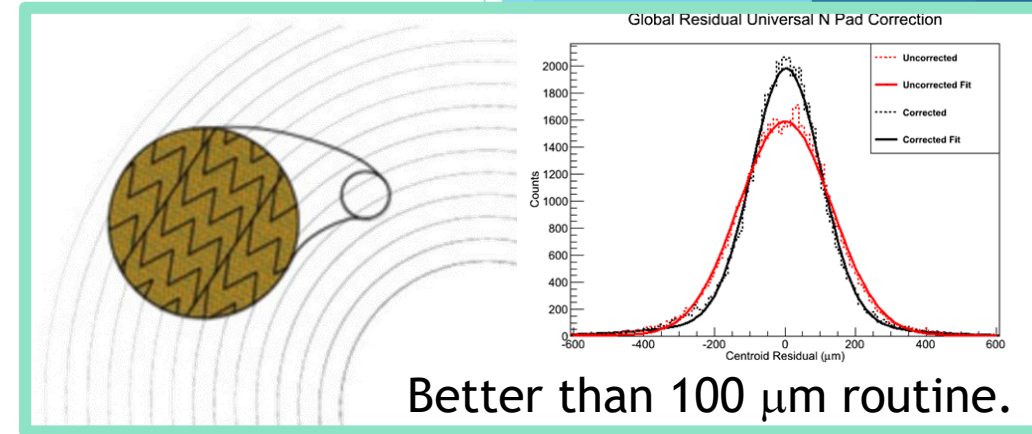
Transfer fields: 4000/4000/100/4000

- ▶ Basic messages from IBF studies remain the same:
 - ▶ Low IBF likes the gain “deep” in the GEMstack.
 - ▶ Make the first GEMs as low as possible gain.
 - ▶ Lowest IBF is the worst resolution limited by statistical fluctuations of earliest gain stages.



Effects of Space Charge on TPC performance

- ▶ The process of measuring trajectories can be factorized:
 - ▶ Position resolution of hits on a pad plane (easy part).
 - ▶ Extrapolating back through the gas volume (hard part).
- ▶ Next generation TPCs feature high rate but suffer from space charge distortions that complicate the extrapolation from the measured coordinate back to the source point.
- ▶ Positive ion space charge effectively “pulls” the electron trajectories toward the center of the TPC.
- ▶ The magnitude of the distortion can be very large:
 - ▶ STAR ~10 cm.
 - ▶ ALICE 10-20 cm.
- ▶ The average deflection can be determined by measurement and calibration to high precision.
- ▶ Final device performance is limited by the FLUCTUATIONS in the deflection (i.e. percentages of the deflection).



ALICE design goal: 200 μm from 4 mm pads.

Goal of the Study

- ▶ Make a (correct & precise) calculation of the mean deflections of ionization as they traverse the TPC.
- ▶ Apply all sources of fluctuations onto the full drift process.
 - ▶ Space charge, of course.
 - ▶ “Normal” fluctuations also!
- ▶ Add uncertainty in the full drift process to the uncertainty in the gain stage.
- ▶ Learn realistic resolution.

Mean Deflections of ionization due to space charge in ALICE @ 50 kHz

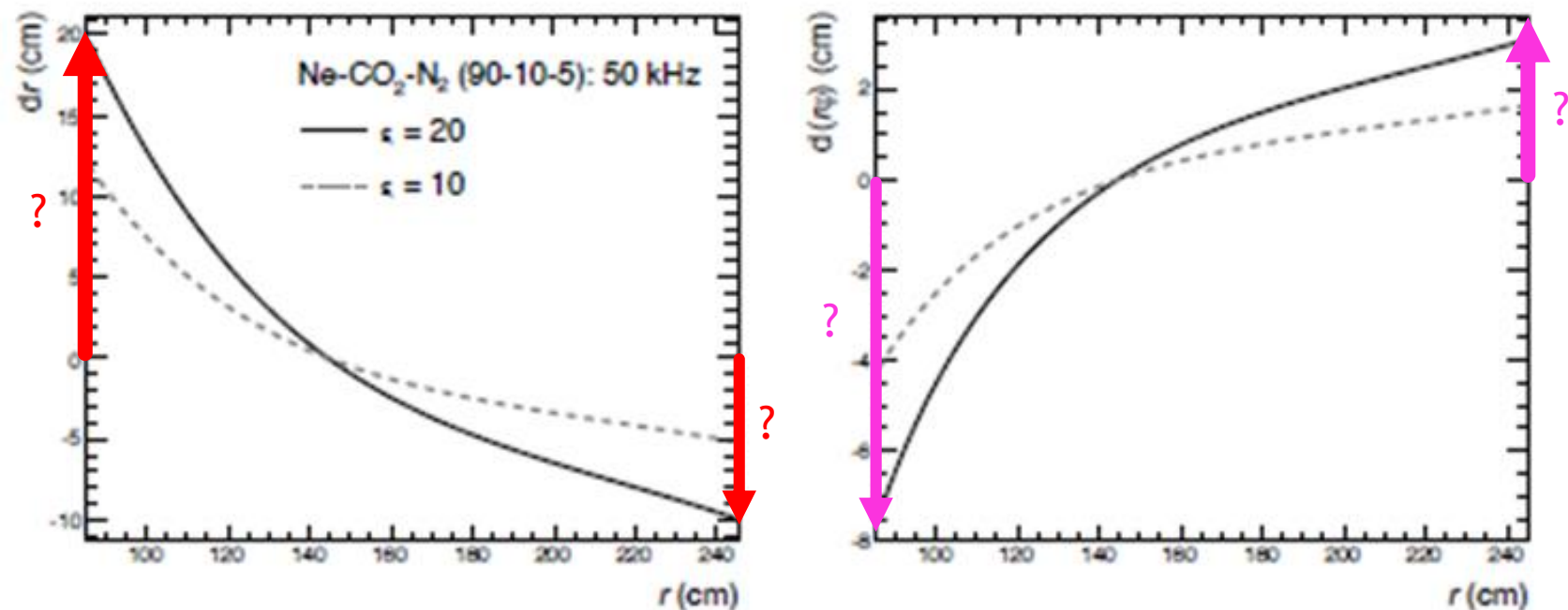


Figure 7.9: Space-point distortions in r (left panel) and $r\phi$ (right panel) as a function of the radial position r close to the central electrode ($z \approx 0$ cm) for Ne-CO₂-N₂ (90-10-5), $R_{\text{int}} = 50$ kHz, $\epsilon = 10$ and 20.

$$\Delta v_d = \left(\frac{\partial v_d}{\partial E} \Delta E + \frac{\partial v_d}{\partial T} \Delta T + \frac{\partial v_d}{\partial P} \Delta P + \frac{\partial v_d}{\partial C_{\text{CO}_2}} \Delta C_{\text{CO}_2} + \frac{\partial v_d}{\partial C_{\text{N}_2}} \Delta C_{\text{N}_2} \right).$$

1st order coefficients:

$$\begin{aligned} \frac{\partial v_d}{\partial E} &= (0.24 \pm 0.02) [\% \text{ cm/V}] \\ \frac{\partial v_d}{\partial T} &= (0.31 \pm 0.02) [\% / K] \\ \frac{\partial v_d}{\partial P} &= (-0.13 \pm 0.01) [\% / \text{Torr}] \\ \frac{\partial v_d}{\partial C_{\text{CO}_2}} &= (-6.60 \pm 0.29) [\% / \%) \\ \frac{\partial v_d}{\partial C_{\text{N}_2}} &= (-1.73 \pm 0.23) [\% / \%) \end{aligned}$$

2nd order coefficients:

$$\begin{aligned} \frac{\partial^2 v_d}{\partial E^2} &= -0.001 \pm 0.009 [\% \text{ cm/V}] \\ \frac{\partial^2 v_d}{\partial T^2} &= -0.001 \pm 0.006 [\% / K] \\ \frac{\partial^2 v_d}{\partial P^2} &= -0.001 \pm 0.001 [\% / \text{Torr}] \\ \frac{\partial^2 v_d}{\partial C_{\text{CO}_2}^2} &= 0.33 \pm 0.95 [\% / \%) \\ \frac{\partial^2 v_d}{\partial C_{\text{N}_2}^2} &= 0.15 \pm 0.64 [\% / \%) \end{aligned}$$

ALICE

Implemented Code

Size as Constructor Argument

Temporarily public
(testing only)

Return Functions

```
class Spacecharge
{
public:
    Spacecharge(double a=30, double b=80, double L=80);
    virtual ~Spacecharge() {}

    void Verbosity(int v) {verbosity=v;}
    double Rmn (int m, int n, double r); //Rmn function from Rossegger
    double Rmn1(int m, int n, double r); //Rmn1 function from Rossegger
    double Rmn2(int m, int n, double r); //Rmn2 function from Rossegger
    double RPrime(int m, int n, double a, double r); // RPrime function from Rossegger

    double Rnk(int n, int k, double r); //Rnk function from Rossegger

    double Ez (double r, double phi, double z, double r1, double phil, double z1);
    double Er (double r, double phi, double z, double r1, double phil, double z1);
    double Ephi(double r, double phi, double z, double r1, double phil, double z1);

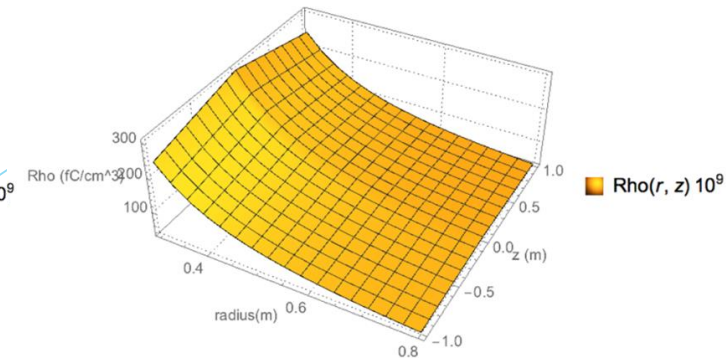
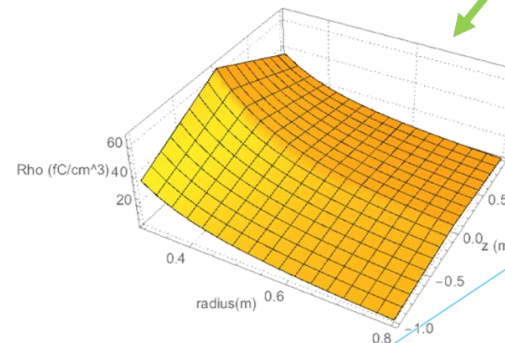
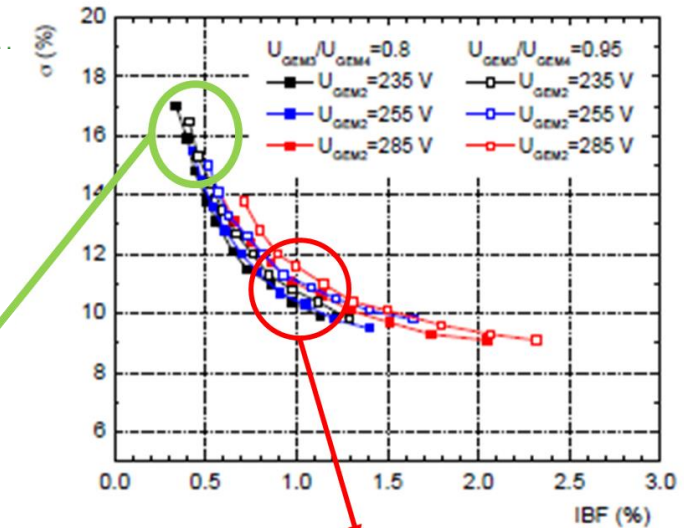
protected:
```

- ▶ Ez and Er implementation are unchanged since last report.
- ▶ Help from Dave Morrison provides implementation necessary for Ephi.
 - ▶ Currently dummy since we'll start with phi-symmetric space charge.
- ▶ Returns are effectively Greene's Functions that provide a value of a field at (r, ϕ, z) in response to a point charge placed at (r_1, ϕ_1, z_1) .
- ▶ To learn the total field, one must integrate the Greene's function over the charge:

$$\vec{E}_r(\vec{x}) = \int E_r(\vec{x}, \vec{x}') \rho(\vec{x}') dV'$$

$$\vec{E}_z(\vec{x}) = \int E_z(\vec{x}, \vec{x}') \rho(\vec{x}') dV' + 400 \frac{V}{cm}$$

Requires Proof Matches ALICE!



Basic Approach to Solving the Cylinder

- The problem at hand is this: $\Delta G(\vec{x}; \vec{x}') = -\delta(\vec{x} - \vec{x}'),$ (5.13)

$$\left[\frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial^2}{\partial \phi^2} + \frac{\partial^2}{\partial z^2} \right] G(r, \phi, z; r', \phi', z') = -\frac{\delta(r - r')}{r'} \delta(\phi - \phi') \delta(z - z'), \quad (5.14)$$

- Our solution begins with solving the homogeneous equation to provide a basis set of functions for the full solution:

$$\Delta \Phi = 0, \quad \left(\frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial^2}{\partial \phi^2} + \frac{\partial^2}{\partial z^2} \right) \Phi(r, \phi, z) = 0, \quad \Phi(r, \phi, z) = R(r) \Phi(\phi) Z(z).$$

Periodicity set $m=0,1,2,3,\dots$ $\Phi_m(\phi) = C_m e^{im\phi} = A_m \cos(m\phi) + B_m \sin(m\phi)$ with $m \in \mathbb{Z}$.

$$\frac{R_{rr}}{R} + \frac{1}{r} \frac{R_r}{R} - \frac{m^2}{r^2} = -\frac{Z_{zz}}{Z} = \begin{cases} -\beta^2, & \text{case I;} \\ \beta^2, & \text{case II.} \end{cases}$$

Solution without boundary conditions applied:

$$Z_m(z) = C_m \cosh(\beta z) + D_m \sinh(\beta z), \\ R_m(r) = E_m J_m(\beta r) + F_m Y_m(\beta r).$$

Constants formulated to explicitly vanish at $r=a$

$$R_{mn}(r) = Y_m(\beta_{mn}a) J_m(\beta_{mn}r) - J_m(\beta_{mn}a) Y_m(\beta_{mn}r).$$

Vanishing at $r=b$ forces β to become discrete.

How to Make This Plot:

- ▶ Choose an IBF operating point and collision rate (raw not triggered)
- ▶ Use standard form for the space charge density under these conditions.
- ▶ Select $r=a$.
- ▶ Integrate:

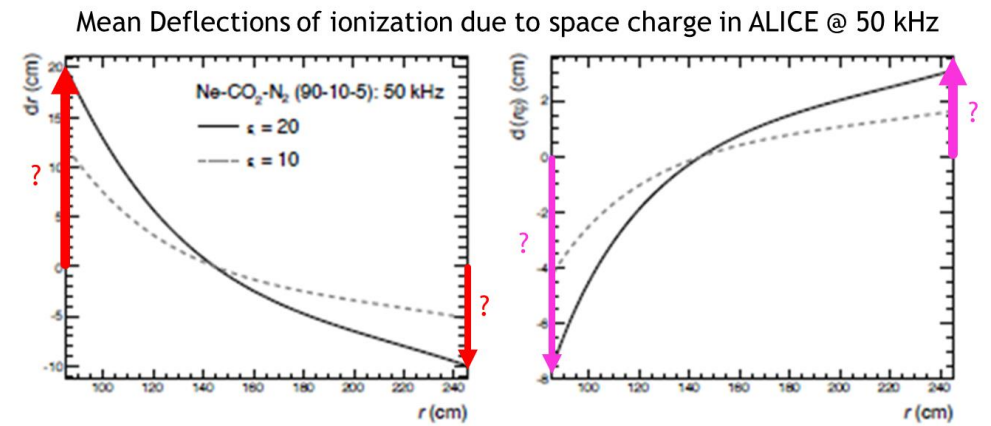
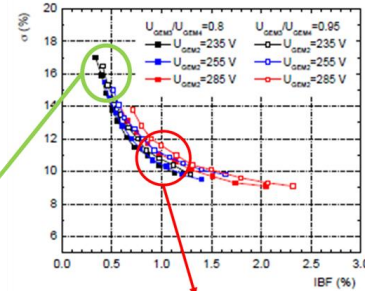
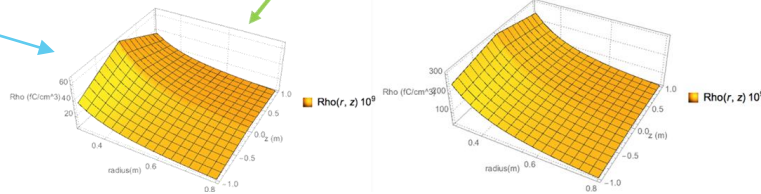


Figure 7.9: Space-point distortions in r (left panel) and $r\phi$ (right panel) as a function of the radial position r close to the central electrode ($z \approx 0$ cm) for Ne-CO₂-N₂ (90-10-5), $R_{int} = 50$ kHz, $\epsilon = 10$ and 20.

$$dr = \int \frac{E_r}{E_z} dz = \int \frac{\int E_r(\vec{x}, \vec{x}') \rho(\vec{x}') dV'}{400 \frac{V}{cm} + \int E_z(\vec{x}, \vec{x}') \rho(\vec{x}') dV'} dz$$

Talk on Space Charge Calculations given by Carlos...

NOTE: I have relegated discussions of “standard” TPC design parameters (drift velocity, diffusion, field uniformity, ...) to backup slides.

Title

Overview

- ▶ **THANK YOU!!** I anticipate that it will be extremely valuable to bring a broad discussion of the still-evolving sPHENIX TPC conceptual design to a broad audience of experts.
- ▶ What I hope to receive from the outside experts:
 - ▶ Validation (where appropriate) of the considerations that we've made thus far.
 - ▶ Corrections (where appropriate) of mistakes that we've made.
 - ▶ Suggestions for items that require more thought.
- ▶ Three presentations to be made:
 - ▶ TK Hemmick:
 - ▶ Overview of the project.
 - ▶ Detailed considerations driving our design.
 - ▶ Carlos Perez:
 - ▶ Calculations of Space Charge Effects.
 - ▶ Alan Dion
 - ▶ Simulations of detector performance.

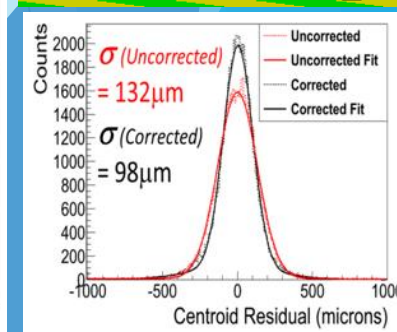
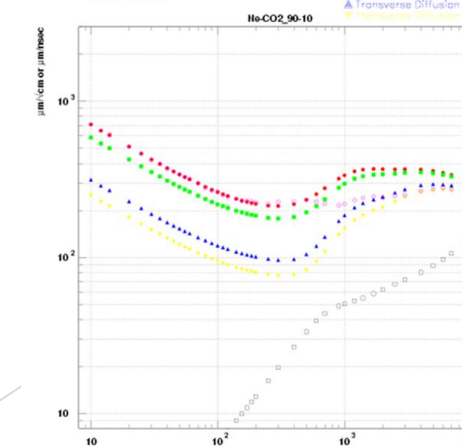
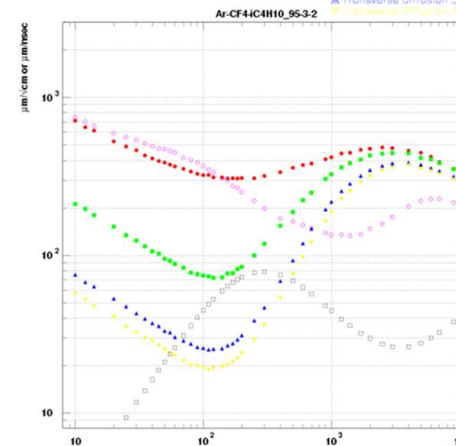
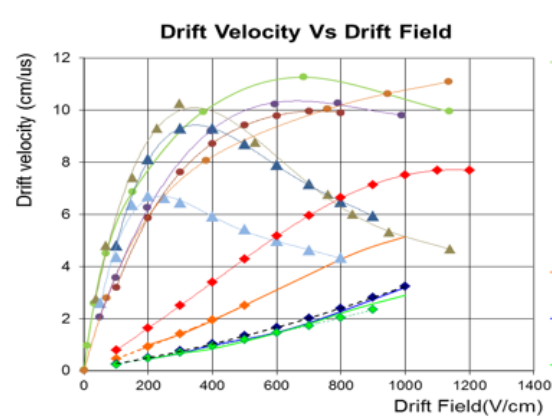
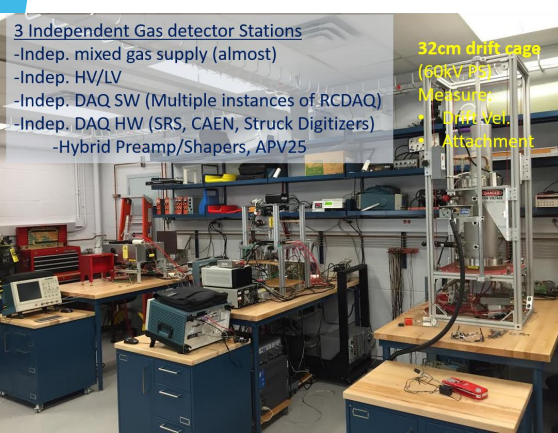
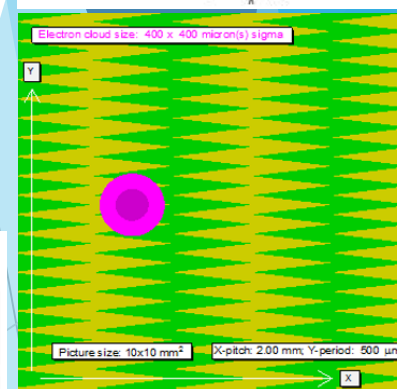
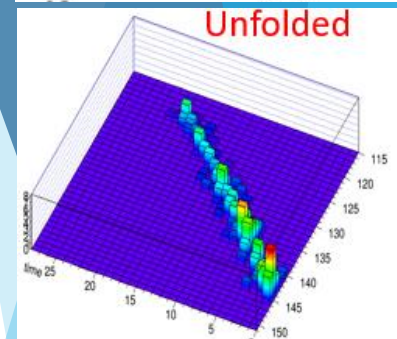
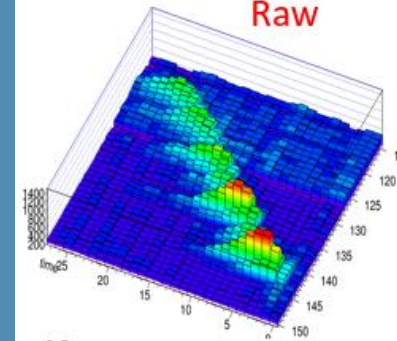
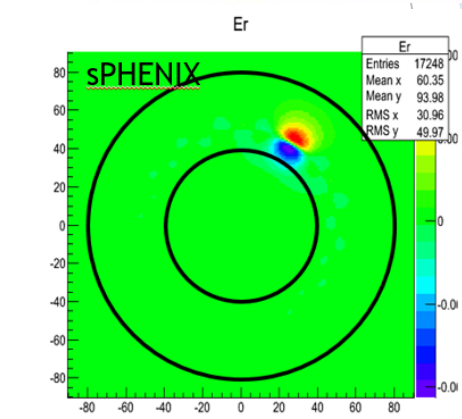
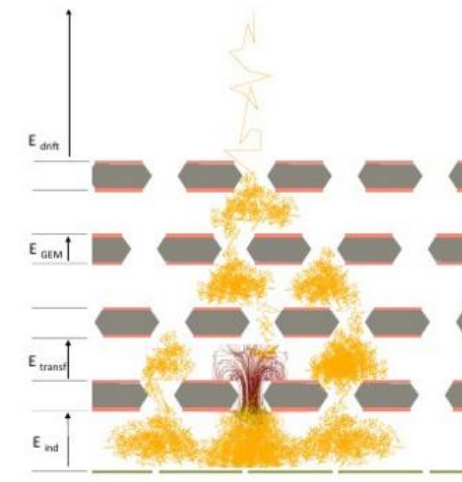
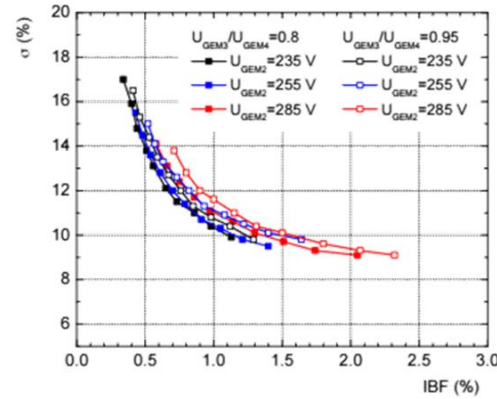
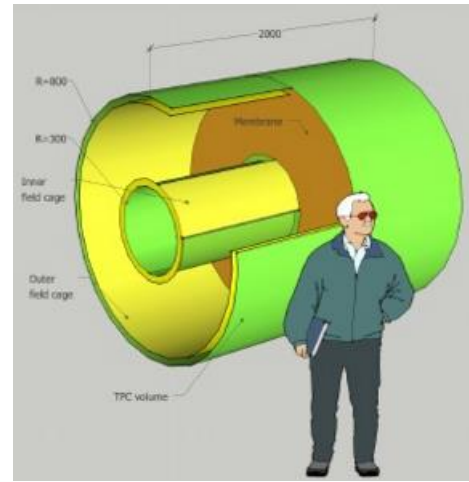
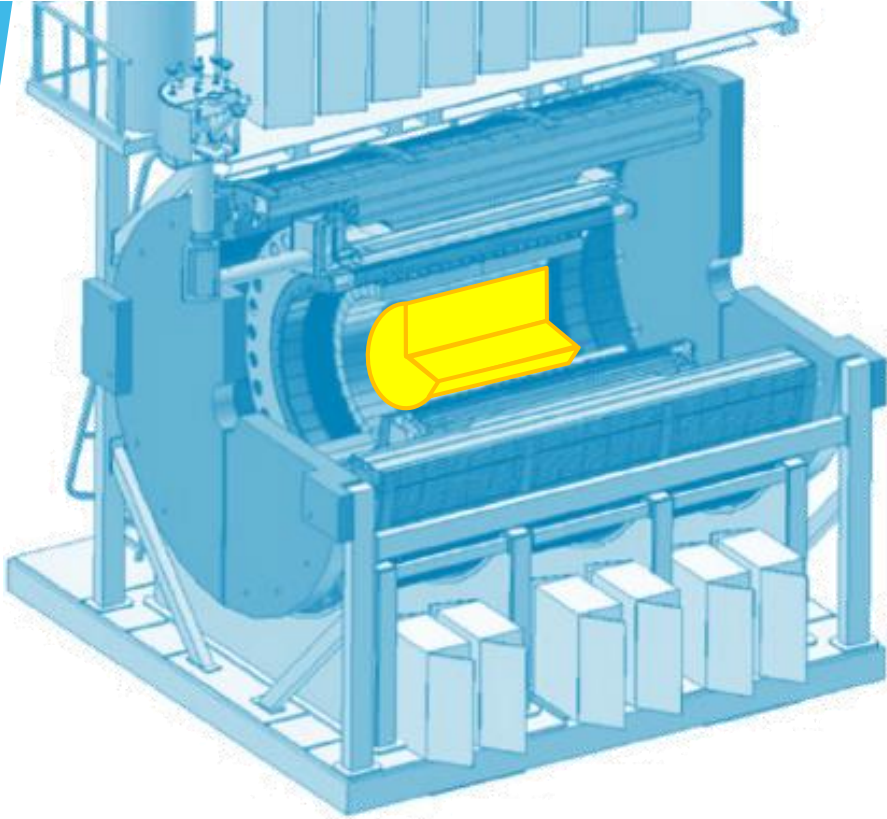
NOTE: This talk respects the age diversity of our crew.
I request patience of experts on some of the slides...

TPC/HBD Test Beam Experiment April 2016



R&D Capabilities

R&D Capability



eRD6 - EIC R&D

► “Tracking/PID Consortium”

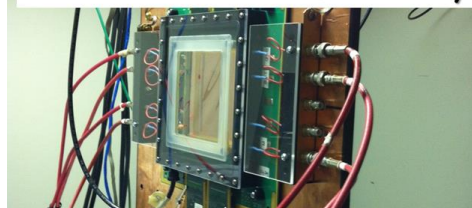
► BNL, FIT, UVa, SBU, Yale (LLNL, TU, WIS)

► Varied R&D topics w/ MPGD devices:

- Mini-drift pad chambers.
- Chevron readout
- TPC/HBD prototype
- Large-scale/Low mass GEM trackers
- CsI RICH for High-momentum PID
- 3-coordinate pad readout
- Hybrid gain stage for low IBF TPC devices

► Staged large test beam expt @ FTBF

Brookhaven National Laboratory



Yale University



University of Virginia

Florida Institute of Technology

Stony Brook University



Shift Crew 1



Fermilab Test Beam Facility

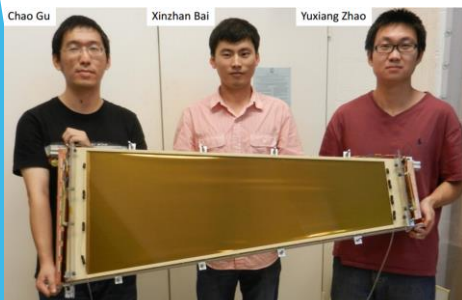
Shift Crew 2



FERMILAB

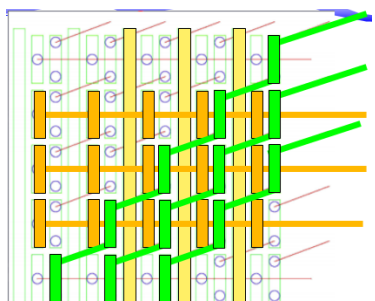
TEST BEAM

FACILITY



Largest Compass-style Chamber

3-coords from single foil

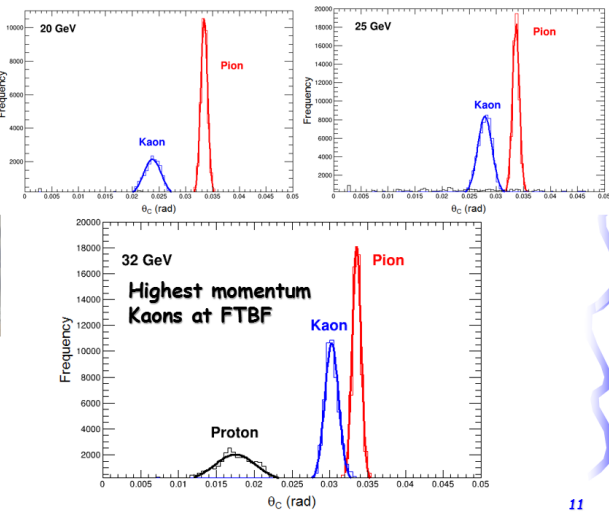


Tra

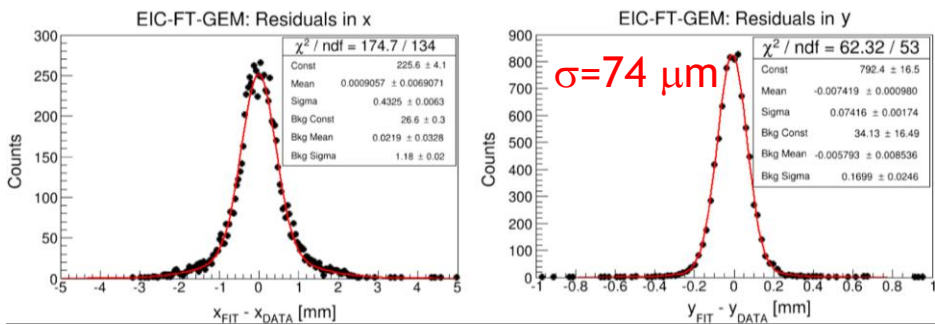
Note: Photo shows Beam Shifters only!

Assorted eRD6 Results (most published)

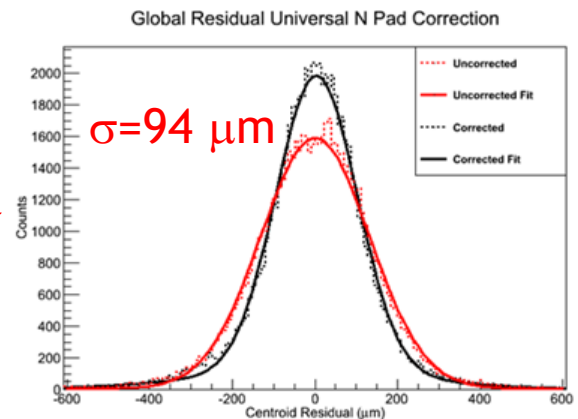
RICH-based PID



Large Chamber w/ small angle stereo

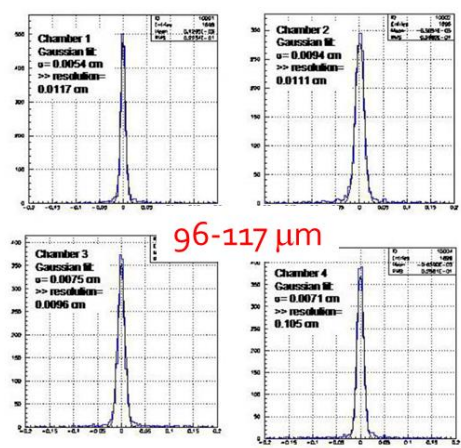


Small TPC w/ Chevrons

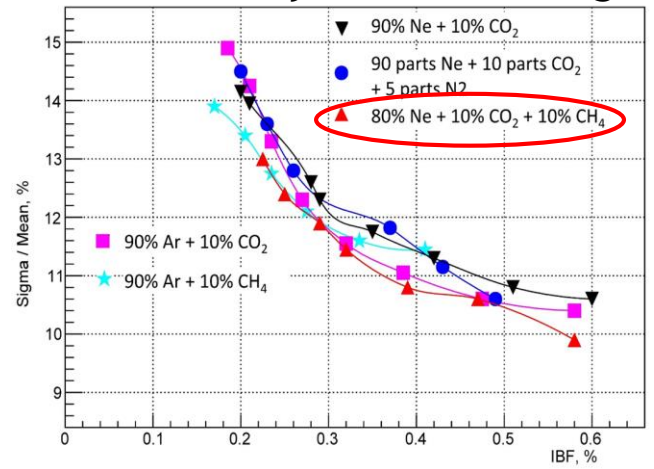


Most relevant to us?

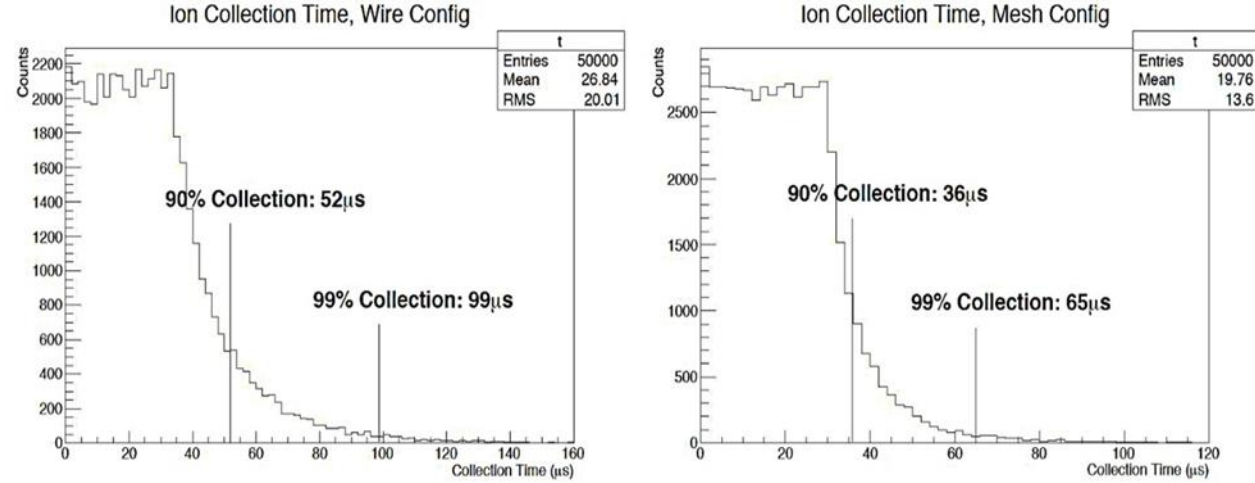
3-coordinate



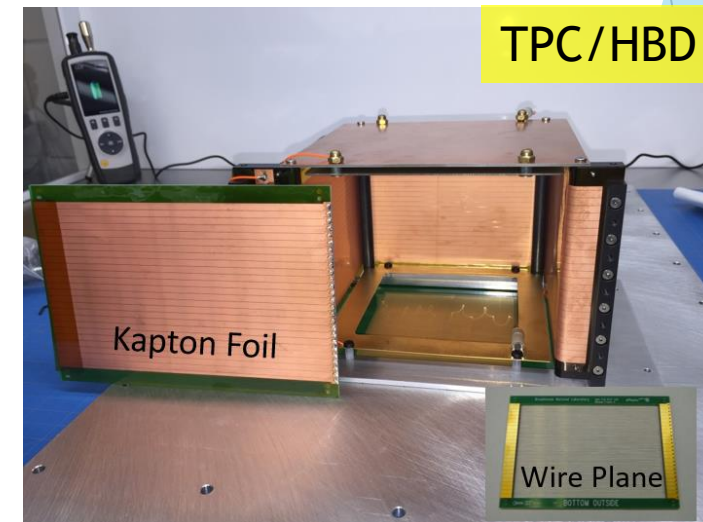
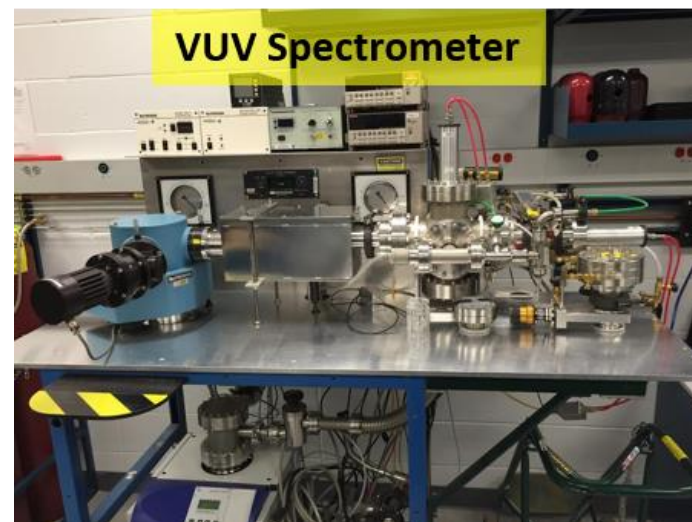
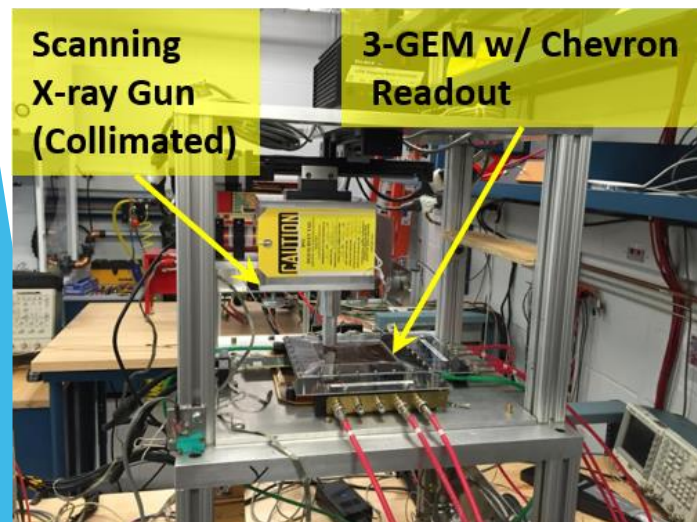
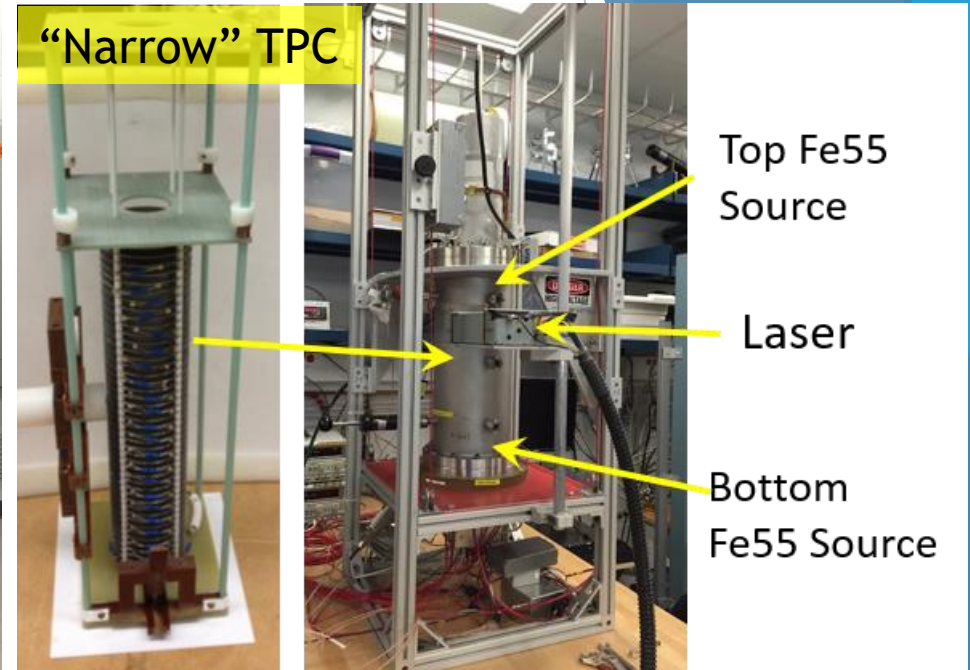
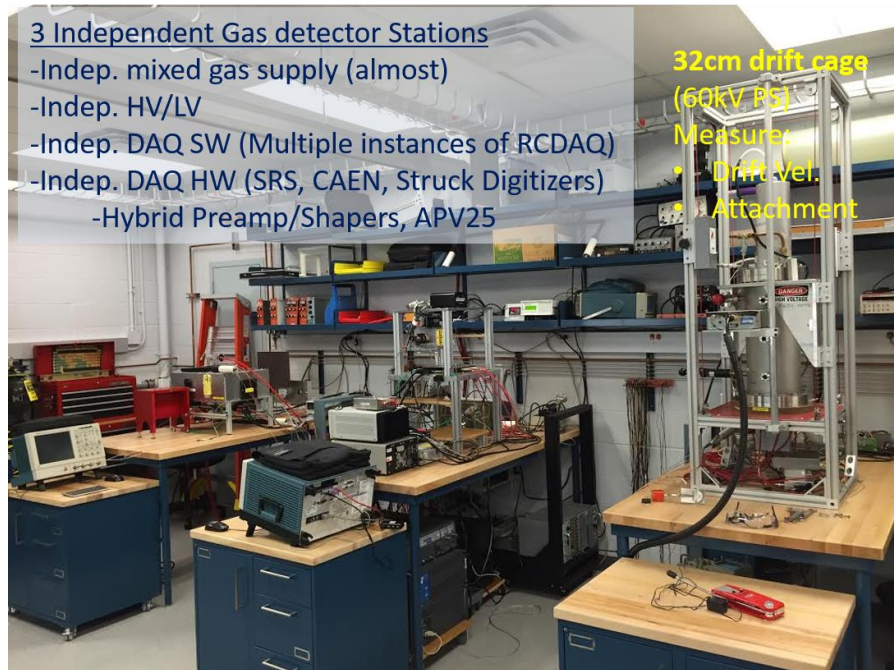
IBF with Hybrid Gain Stage



H. Wieman Grid simulation

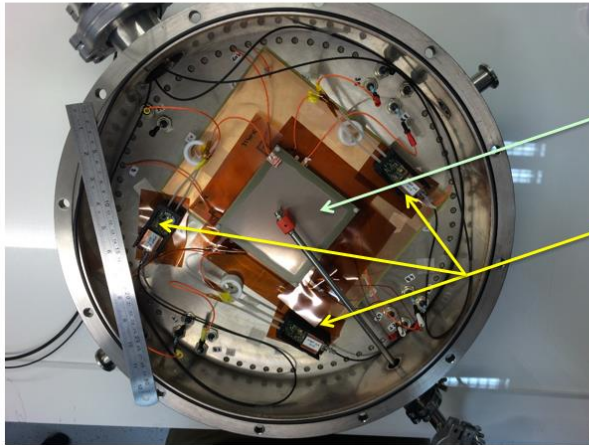


Facilities at BNL (co-occupied by Yale)



Facilities at WIS

IBF test box



It has new inhabitants:

Standard 3(expandable)
framed CERN GEMs

Zagreb-made floating
picoamperimeters.

They are sensitive to
measure current from a
5kHz iron source.
(Signals are weak).

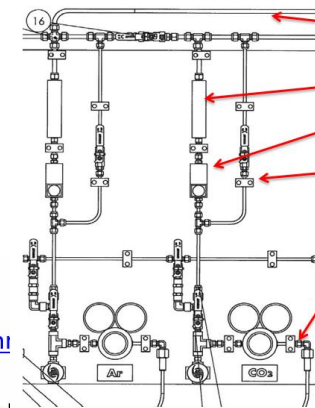
Zagreb pA's



www.picologic.hr

Battery powered
or DC powered.

Gas system



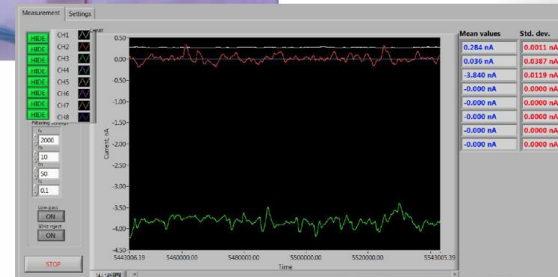
3 output lines (2 shown)
Configurable
Visual control
Fully computer controlled
2% accuracy
Fast fill up
4 input lines
(two shown)



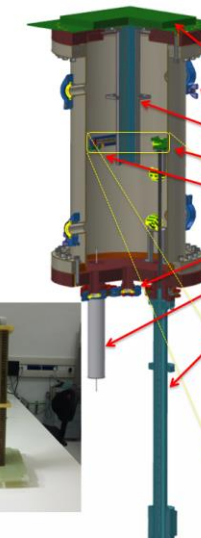
The clean room.



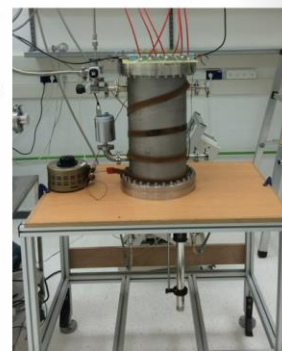
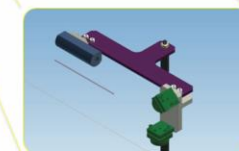
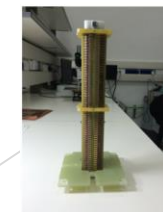
- ▶ Complete capabilities for gas characterization & IBF.
- ▶ BTW—Yale and SBU are not exactly devoid of relevant equipment



New test cell



Assembly of 10x10cm CERN GEMs
View ports, laser injection window
Field cage
Lens and mirrors for 266nm
Radioactive source
Vacuum ports
HV feed through
Linear transformer



Size & Performance

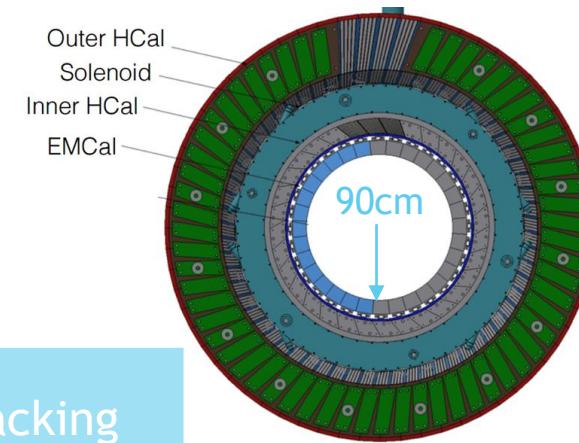
Detector Specifications

- ▶ Mechanical Constraints (magnet/EMCal-driven)
 - ▶ EMCal Mechanical constraint @ $r=90\text{cm}$.
 - ▶ Physics = coil aspect ratio: $|\eta| < 1.1$ or $Length \approx Diameter$
 - ▶ **Current Tracker Confining Volume: Length = Diameter = 160cm.**
- ▶ Physics program accomplished via two toughest constraints:
 - ▶ Mass resolution sufficient to resolve Upsilon States.
 - ▶ **$\sigma_m < 100 \frac{\text{MeV}}{c^2}$ @ $m \approx 9 \frac{\text{GeV}}{c^2}$** ← Outer Tracking
 - ▶ DCA Resolution sufficient for tagging heavy flavor secondary vertices.
 - ▶ $c\tau(D) = 123 \mu\text{m}; c\tau(B) = 457 \mu\text{m}$
 - ▶ **$\sigma_{DCA} < 100 \mu\text{m}$** ← Inner Vertex
- ▶ Environmental constraints:
 - ▶ **Central Au+Au multiplicity @ full RHIC Energy.**
 - ▶ **Full RHIC-II Luminosity (100 kHz raw, 15 kHz w/in vertex)**

"...we anticipate that the features and experience gained with this device might provide the basis for a "day-1" detector at a future EIC, independent of where the new facility will be sited. It is envisioned that this new collaboration will consider the possible evolution toward such a detector as part of its mission."

--Berndt Mueller

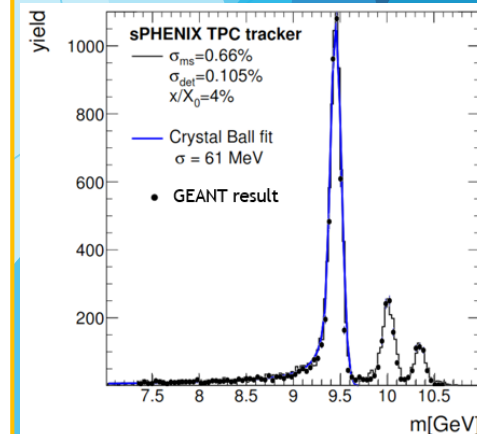
Mechanical Constraint



Physics Constraint

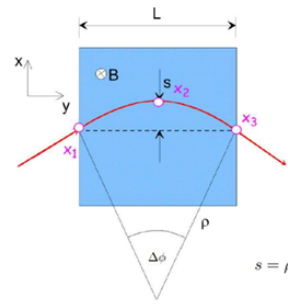


Radius 20cm-78cm
Length +/- 80 cm



Momentum Resolution-I

Position Resolution:
(Silicon best)

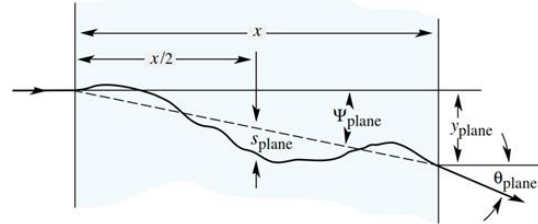


$$s = \rho(1 - \cos \frac{\Delta\phi}{2}) \approx \rho(1 - (1 - \frac{1}{2} \frac{\Delta\phi^2}{4})) = \rho \frac{\Delta\phi^2}{2} \approx \frac{0.3}{8} \frac{L^2 B}{p_T}$$

$$\frac{\sigma_{p_T}}{p_T} = \frac{\sigma_s}{s} = \frac{8\sigma_s}{0.3L^2 B} p_T$$

$$\frac{\sigma_{p_T}}{p_T} = \sqrt{\frac{720}{(N+4)}} \frac{\sigma_x}{0.3L^2 B} p_T$$

Multiple Scattering:
(Hybrid better)



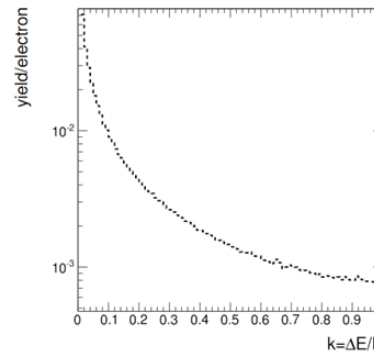
$$\phi_0 = \frac{13.6 \text{ MeV}}{\beta c p_T} z \sqrt{\frac{L}{X_0}} [1 + 0.038 \ln \frac{L}{X_0}]$$

$$\frac{\sigma_{p_T}^{ms}}{p_T} = \frac{0.052}{\beta B L} \sqrt{\frac{L}{X_0}} [1 + 0.038 \ln \frac{L}{X_0}].$$

3 Dimensions:

$$\frac{\sigma_p}{p} = \sqrt{\left(\frac{\sigma_{ms}}{\sqrt{\sin \theta}}\right)^2 + (\sigma_{det} p \sin \theta)^2 + (\sigma_{\theta}^{det} \cot \theta \sin \theta)^2 + \left(\frac{\sigma_{\theta}^{ms}}{\sqrt{\sin \theta}} \frac{\cot \theta}{p}\right)^2}$$

Bremsstrahlung:
(Hybrid better)



$$k \equiv \frac{\Delta E}{E}$$

$$\frac{d\sigma}{dk} = \frac{A}{X_0 N_A k} \left(\frac{4}{3} - \frac{4}{3} k + k^2 \right)$$

$$N_{\gamma} = \frac{L}{X_0} \left(\frac{4}{3} \ln \frac{k_{max}}{k_{min}} - \frac{4(k_{max} - k_{min})}{3} + \frac{k_{max}^2 - k_{min}^2}{2} \right)$$

Tracking Systems (Practice)

Momentum Resolution calculated for all options from analytic and full Monte Carlo Simulations

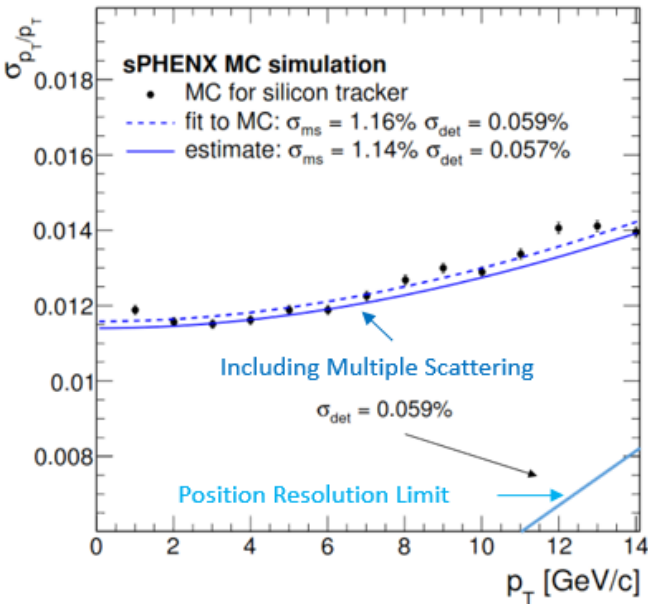
Momentum Resolution-II

Station	Layer	radius (cm)	pitch (μm)	sensor length (cm)	depth (μm)	total thickness $X_0\%$	area (m^2)
Pixel	1	2.4	50	0.425	200	1.3	0.034
Pixel	2	4.4	50	0.425	200	1.3	0.059
S0a	3	7.5	58	9.6	240	1.0	0.18
S0b	4	8.5	58	9.6	240	1.0	0.18
S1a	5	31.0	58	9.6	240	0.6	1.4
S1b	6	34.0	58	9.6	240	0.6	1.4
S2	7	64.0	60	9.6	320	1.0	6.5

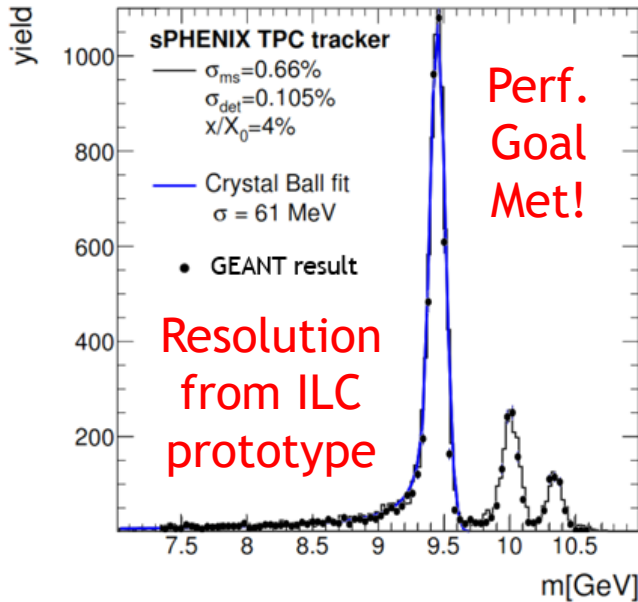
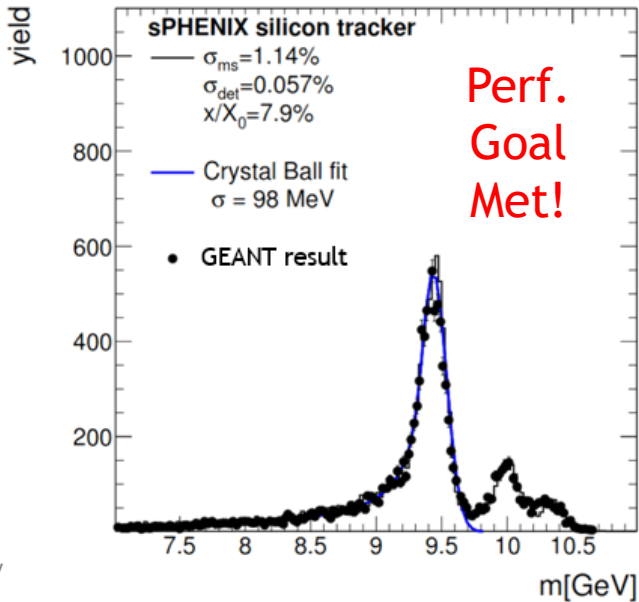
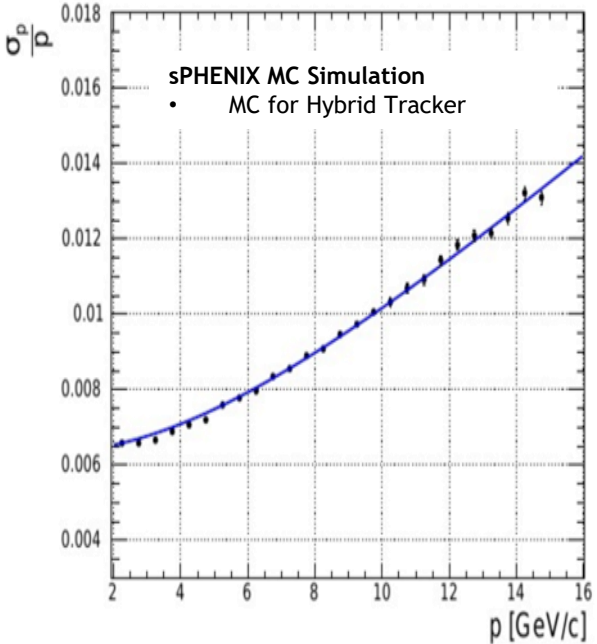
layer	radius (cm)	total thickness % X_0	$\Delta L/L$	c_{ms} (mrad)	σ_{ms} (mrad)
VTX 1	2.7	1.3	0.95	1.8	1.7
VTX 2	4.6	1.3	0.92	1.8	1.7
air	15	0.1	0.73	0.03	0.02
field cage	30	1.0	0.45	1.12	0.5

- Analytic and full Geant simulations performed.
- All results agree remarkably well.
- All options meet the experiment design goal.

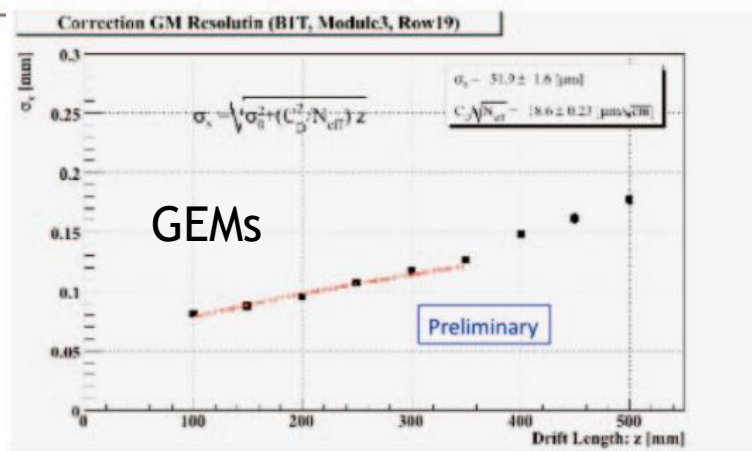
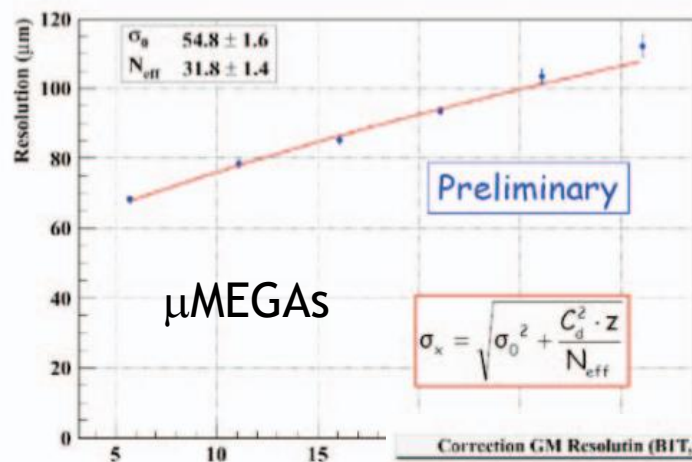
Reference Design



Hybrid: Reuse Pixels + TPC



Design Drivers



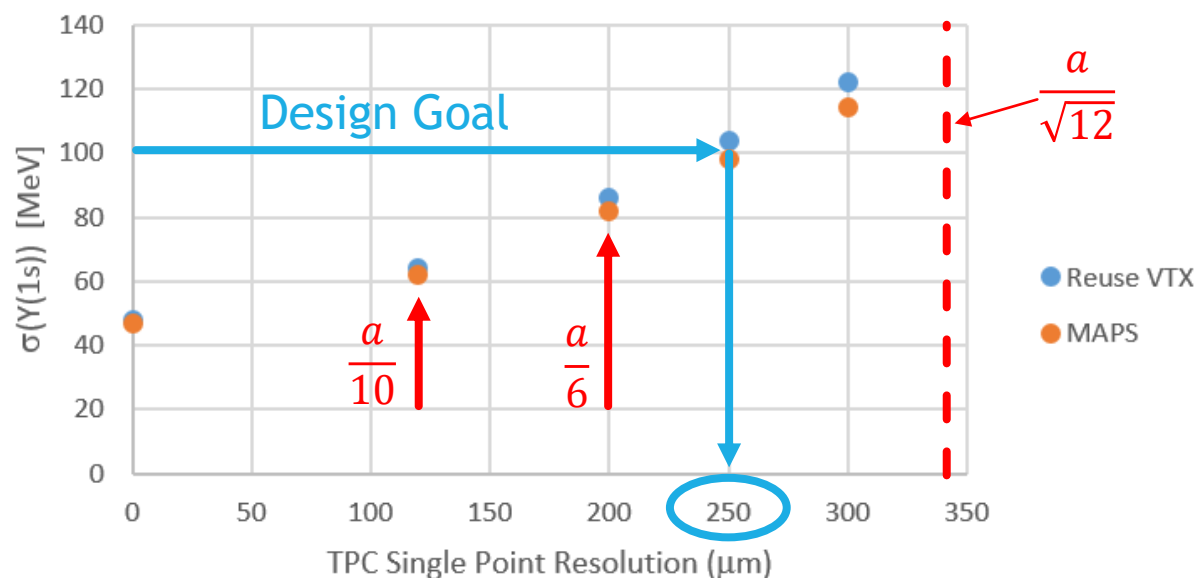
Does not include space charge considerations,

Significant at high rate.

- ▶ ILC R&D results very encouraging.
- ▶ ILC R&D results were used as the basis of the simulations presented previously.
 - ▶ ILC $\sim 150 \mu\text{m}$ after 2.5 meters drift.
 - ▶ sPHENIX requirement $250 \mu\text{m}$ after 80 cm drift.

Hybrid Tracker Option

Degradation of Mass Resolution



- ▶ The Upsilon mass width for the hybrid setup is influenced by the single point resolution.
- ▶ Current calculations assume an RMS resolution of $1/10$ the pad size ($\frac{a}{10}$).
- ▶ The hybrid system will meet the mass resolution goal with an RMS position resolution of $250 \mu\text{m}$.

Talk on Simulations from Alan Dion...

Gateless TPC: Concept & Space Charge

Field Cage Progress

Design Issues—End Plate(s)

- ▶ Big Decision: Bite-sized or chunky?
- ▶ No design exists...
- ▶ Present Cable Count Estimate:
 - ▶ Each module should receive:
 - ▶ 8 HV leads: (prefer custom bundle to reduce capacitance {stored energy} in the cable).
 - ▶ Each sector should receive:
 - ▶ 3-4 DC power leads.
 - ▶ Cooling lines.
 - ▶ Each card should receive:
 - ▶ 2 fibers per card leads to ~200 fibers per sector.
 - ▶ May want to gang cards? Unknown...
- ▶ Needed: Flatness spec while under internal pressure...
- ▶ How to interface this unit to sPHENIX?



	Number	Source
Channels	200,000	Pre-conceptual Design Report
Channels per side	100000	2 sides
Channels per sector	12500	8 sectors per side
Cards per sector	97.65625	Assumes 128 channels per card

Pressurized

- ▶ Concerns about FEA similar to ours.
- ▶ Least deflection at field cages.
- ▶ Our circumstance will be MUCH easier due to smaller size.

FEA calculations of deflection and stress (stress is not shown)

Endplate deflections were calculated with finite element analysis (FEA).

Endplate Support:
outer and inner field cages

Maximum deflection of the model:
0.00867 mm/100N

Calibration: 100N is the force on LP1
due to 2.1 millibar overpressure
ratio of areas: (area of ILD)/(area of LP1) = 21.9

**ILD TPC endplate deflection
for 2.1 millibar overpressure (2190N)**

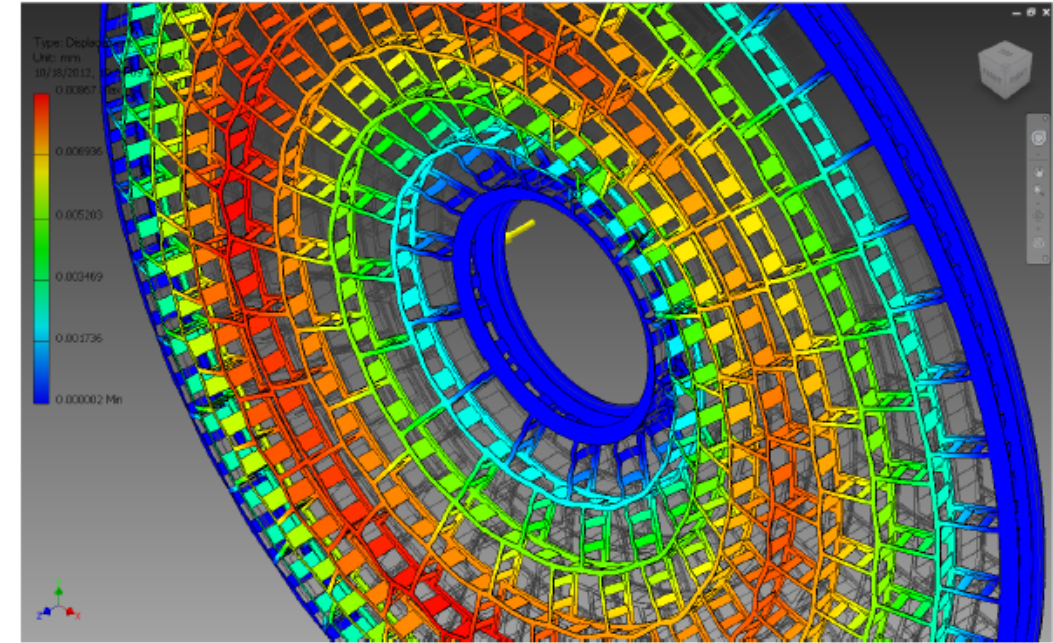
= 0.19 mm

deflection is changed slightly in a new release of the FEA

(Without the space-frame structure, the simple endplate deflects by 50mm.)

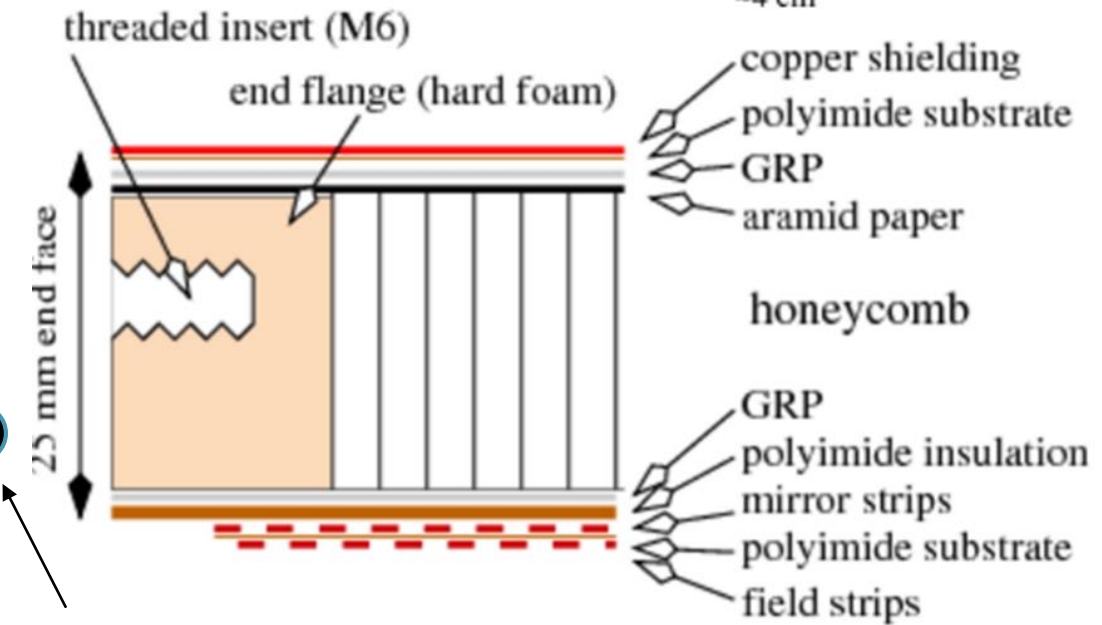
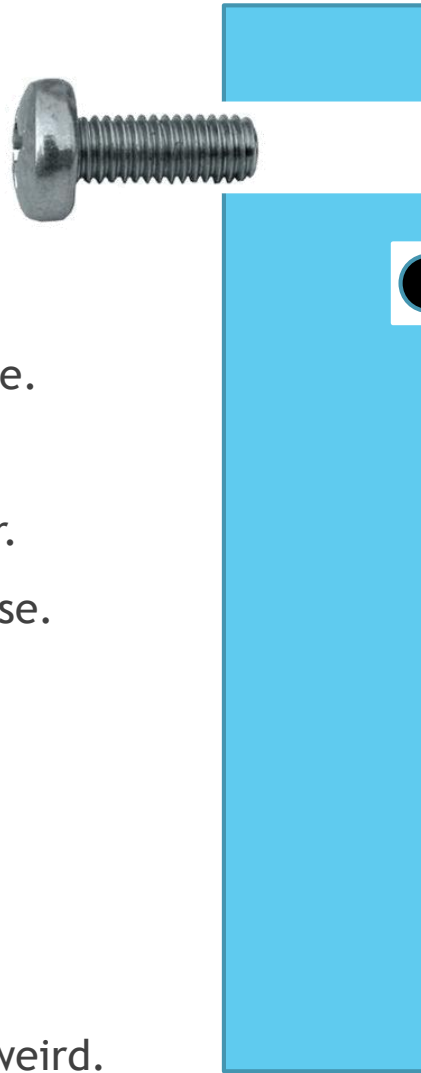
The maximum stress is 9.2 MPa while the yield limit is 241 MPa.

Validation of the FEA for a complicated structure will be discussed.



Design Issues-- Barrel, Unknown

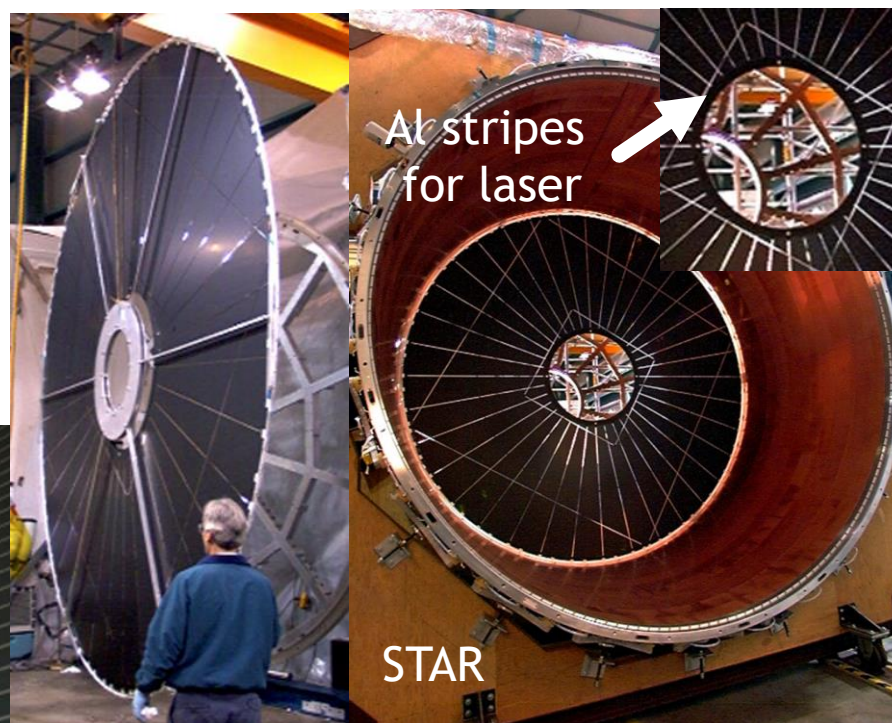
- ▶ How to terminate the field cage?
- ▶ I favor the ILC concept:
 - ▶ Terminating ring
 - ▶ Tapped holes for attachment to end plate.
 - ▶ Aligned via gauge while mandrel turns.
 - ▶ Highest Priority: end plate perpendicular.
 - ▶ Second highest priority: end plate precise.
- ▶ Questions:
 - ▶ How to make the ring?
 - ▶ Multiple pieces?
 - ▶ Gas seal OK at the seams?
 - ▶ Material
Hemmick likes Aluminum...hard foam is weird.



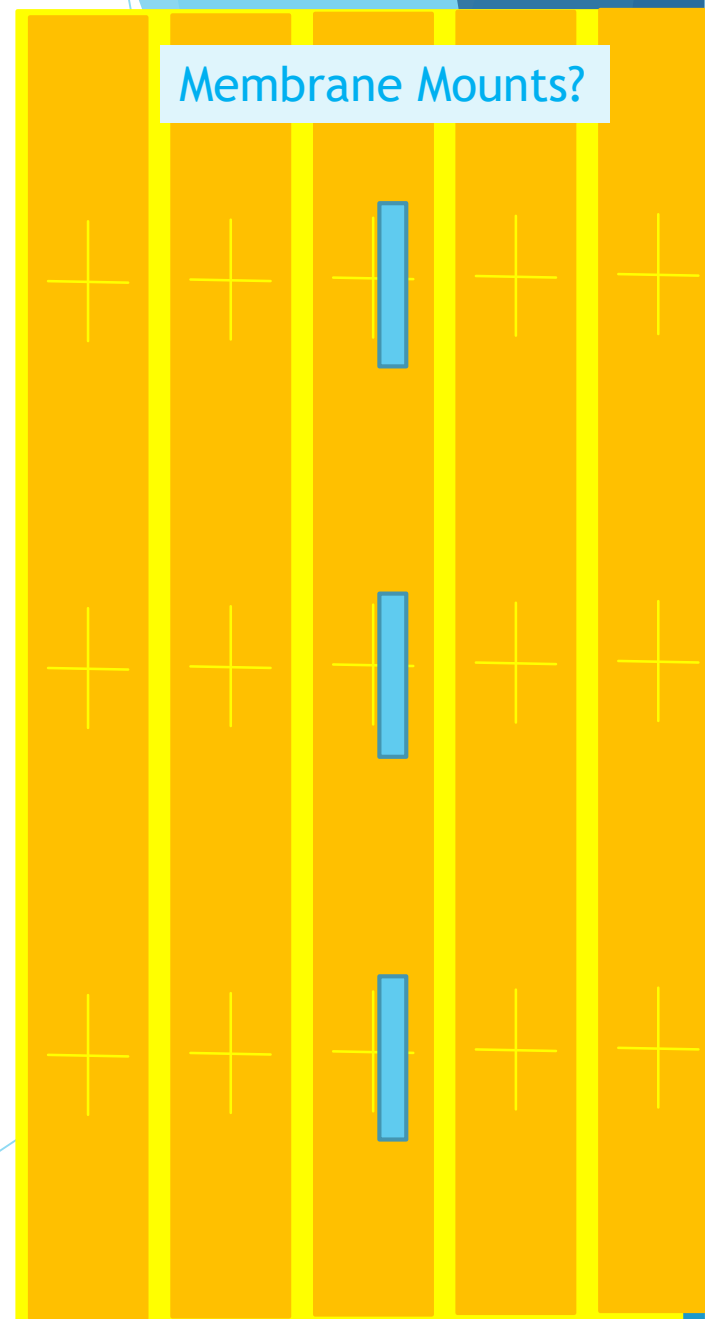
- ▶ High Voltage Contact:
 - ▶ Lead runs down “notch in the honeycomb”.
 - ▶ Lead is between grounded faces.
 - ▶ Must penetrate HVPF layer to reach center stripe!
 - ▶ How do we do this w/o creating spark point?

Design Issues-- Central Membrane

- ▶ How do we position this thing?
 - ▶ Must be accurate (few mil level).
 - ▶ Must be planar.
 - ▶ Concept (works?):
 - ▶ Put fiducial marks on the center stripe during kapton manufacture:
 - ▶ Use the fiducial marks as guides to place mechanical mounts for the central membrane.
- ▶ How do we electrically attach it?
 - ▶ HV lead runs in OUTER shell.
 - ▶ Membrane connects inner/outer shells.
- ▶ Does the membrane warp?
- ▶ Does it move with gas flow?



Membrane Mounts?



Design progress



3D CAD using AutoDesk Inventor Pro
FREE to students and faculty.
Same software used by Rich Ruggiero

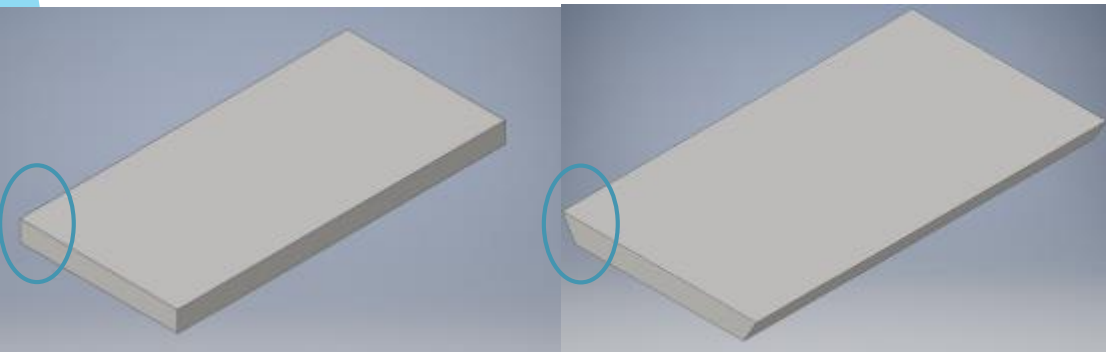
- ▶ Last time we agreed:
 - ▶ $R_{\text{outer}}=80$ cm is too big.
 - ▶ R_{outer} should be somewhere in the range
- ▶ Calculations show that if we design our mandrel to 77cm, we can support either 78 or 76 cm by choosing to cut more or less from our 2" thick foam block.
- ▶ On the right is the wheel assembly in 3D CAD.
- ▶ The central "hub" will be cut from Aluminum plate in the SBU shops.
- ▶ The spokes are 1.5" 8020 extruded material.
- ▶ Three "wheels" make up the inner cage of the mandrel.

NOTE: Last night (2/25/2016), the engineering group selected 78 cm as the TPC outer radius: 10 cm for upgrade plus 1 cm stay clear to each side.

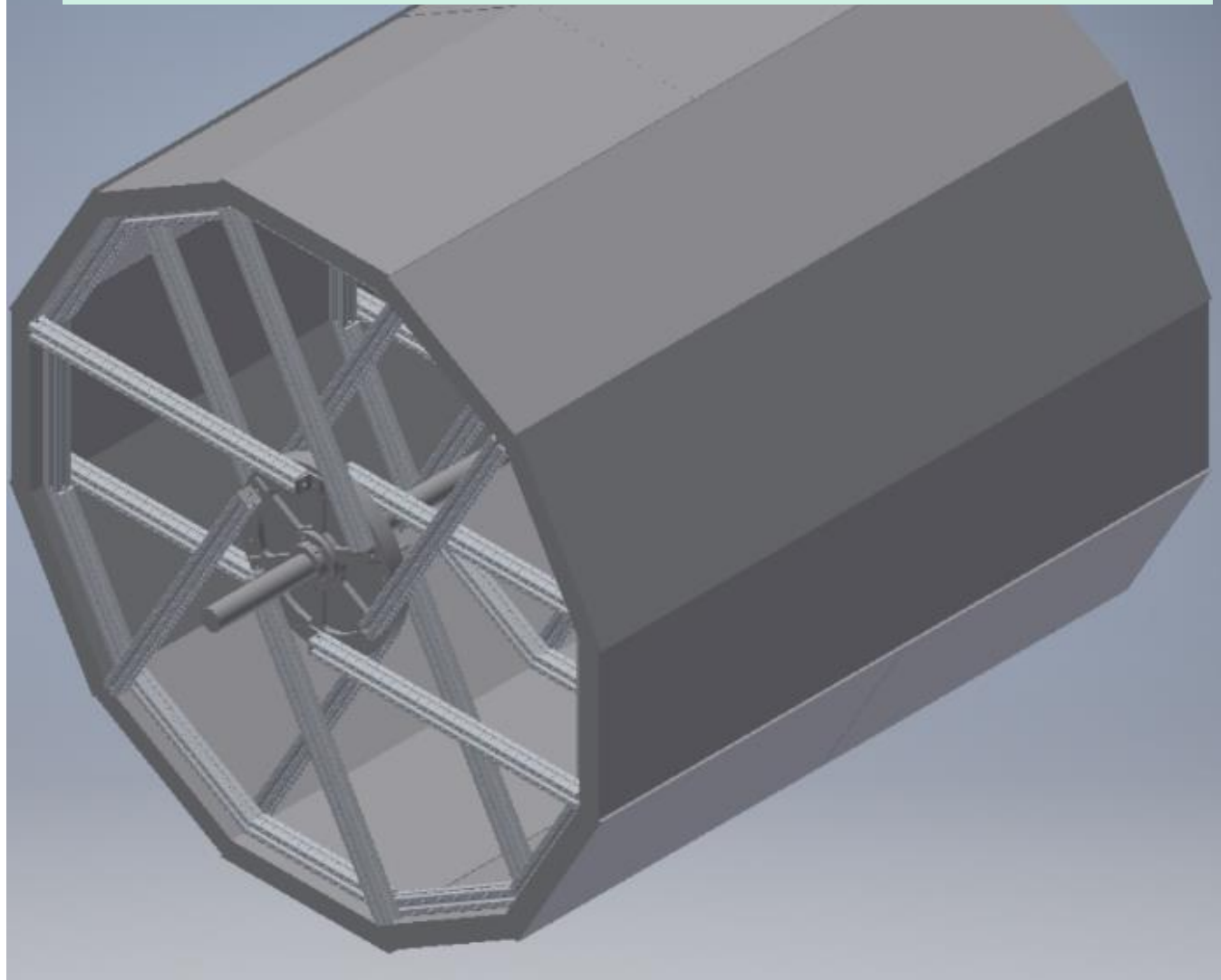


Mandrel CAD Design.

- ▶ Each wheel is held to the precision steel shaft via a collar.
- ▶ The collar is positioned by the SBU shop to be centered in the wheel.
- ▶ The foam blocks are held from the inside via screws (e.g. drywall screws).
- ▶ “Even” numbered blocks: square sides.
- ▶ “Odd” numbered blocks angled sides.
- ▶ Because of the asymmetry, there is a lip at every edge that will be removed.



Samples of 3 densities of foam in hand & “butterboard”
Currently favoring the highest density rohacell



Reminder: Basic concept is to turn (as in lathe) the rohacell foam into a precise cylinder to lay up the field cage walls.

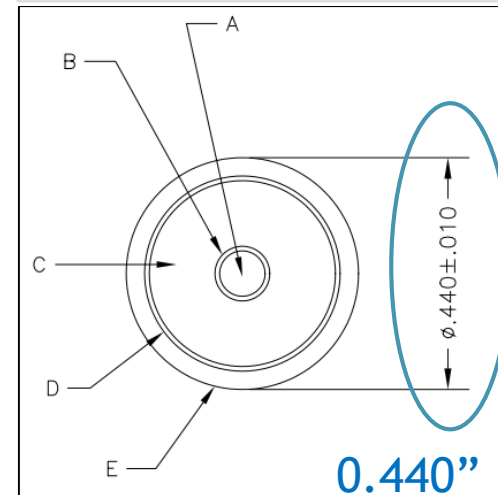
Measure Twice Cut once...

- ▶ We've settled on an outer radius of the device:
 - ▶ 80cm minus 2 cm “stay clear” zone → 78 cm outer radius.
- ▶ QUESTION: What is the exact thickness of the exterior shell?
 - ▶ Since the MANDREL RADIUS is set to the INNER RADIUS size, we should **calculate first** and **then cut metal**.
 - ▶ STAR field cage is 1cm (kapton-hexcell-kapton) and their gas enclosure is also 1cm (aluminum-aluminumhex-aluminum).
 - ▶ Our current design specifies ½” honeycomb.
 - ▶ Set by HV cable diameter... should be driven by mechanical stability.
 - ▶ Sturdier than STAR.
 - ▶ Want to know more before cutting metal...

Dielectric Sciences, Inc.
A High Voltage Technology Group Company

Specifications

Voltage	30 KVAC 100 KVDC
Cable Type	1-Conductor Cable
No. of Conductors	1
Diameter	0.440 in
Gauge	16 AWG
Conductor Material	Tin-plated Copper
Shield	Tin-coated Copper Braid
Insulation Material	Polyethylene
Jacket Material	PVC



LEGEND

- A. #16 AWG (19/29) T.C.
- B. SEMICON POLYETHYLENE TO $\phi.100$
- C. INSULATING POLYETHYLENE TO $\phi.360 \pm .010$
- D. BRAIDED SHIELD, #34 AWG T.C. , 90% COV
9 ENDS, 24 CARRIER
- E. JACKET: PVC: BLACK

NOTES:

- 1. TEST VOLTAGE: 110KVDC— 10 MINUTES
- 2. JACKET SPARK TEST: 5KV

QUESTION: How do you simulate Mechanics of Honeycomb materials in CAD?

Chat with the experts:



▶ Hemmick:

- ▶ Surely we don't simulate the full details of the honeycomb in CAD...
- ▶ Do we go from isotropic to orthotropic material?



▶ Don Lynch:

- ▶ Indeed, you cannot simulate the full honeycomb, you must work around it.
- ▶ Orthotropic is likely the right way to proceed.



▶ Rich Ruggiero:

- ▶ Agreed, you should not input a full honeycomb, not only will the modeling fail to converge, but the file will take forever to render.
- ▶ I'll forward your mail to Anatoli.

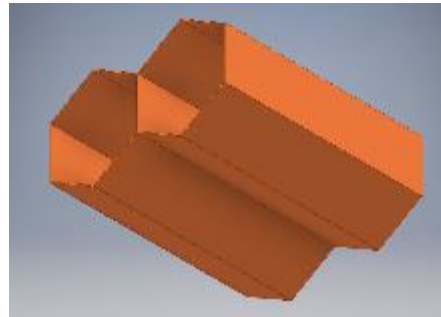


▶ Anatoli Gordeev:

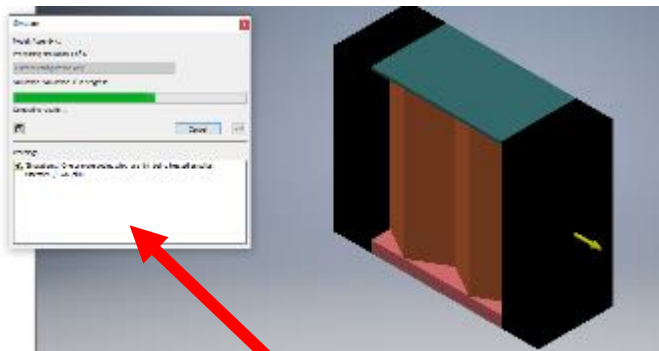
- ▶ In ATLAS (silicon) we measured the parameters that we input to CAD.

Surf the Web

- ▶ Article from China:
 - ▶ You can “measure” honeycomb properties by making a CAD of only 1-2 cells.
 - ▶ **Drat!** Autodesk Inventor throws warnings since the sides are still too thin.



Two-cell CAD



⚠ [Simulation: 1] One or more bodies which are thin being treated as solids:
Assembly1 / TwoCells:1

HexWeb™ HONEYCOMB SANDWICH DESIGN TECHNOLOGY

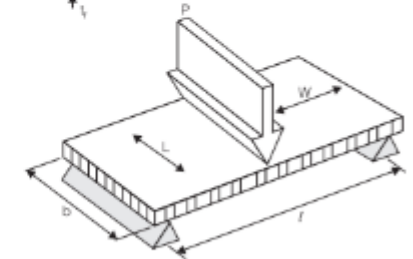
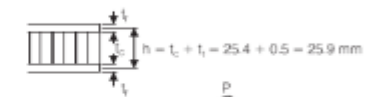
SAMPLE PROBLEMS BASED ON A STANDARD HEXLITE 220 PANEL

Configuration and Data:

Facing Skins	Aluminium 5251 H24
Thickness t_f and t_b	= 0.50mm
and from Appendix II	
Yield Strength	= 150 MPa
E_f Modulus	= 70 GPa
Poissons Ratio μ	= 0.33
Core	5.2 - 1/4 - 3003
Thickness t_c	= 25.4 mm
and from Appendix I	
E_c Modulus	= 1000 MPa
Longitudinal shear	= 2.4 MPa
G_x Modulus	= 440 MPa
Transverse shear	= 1.5 MPa
G_w Modulus	= 220 MPa
Stabilized Compression	= 4.6 MPa

Simply Supported Beam

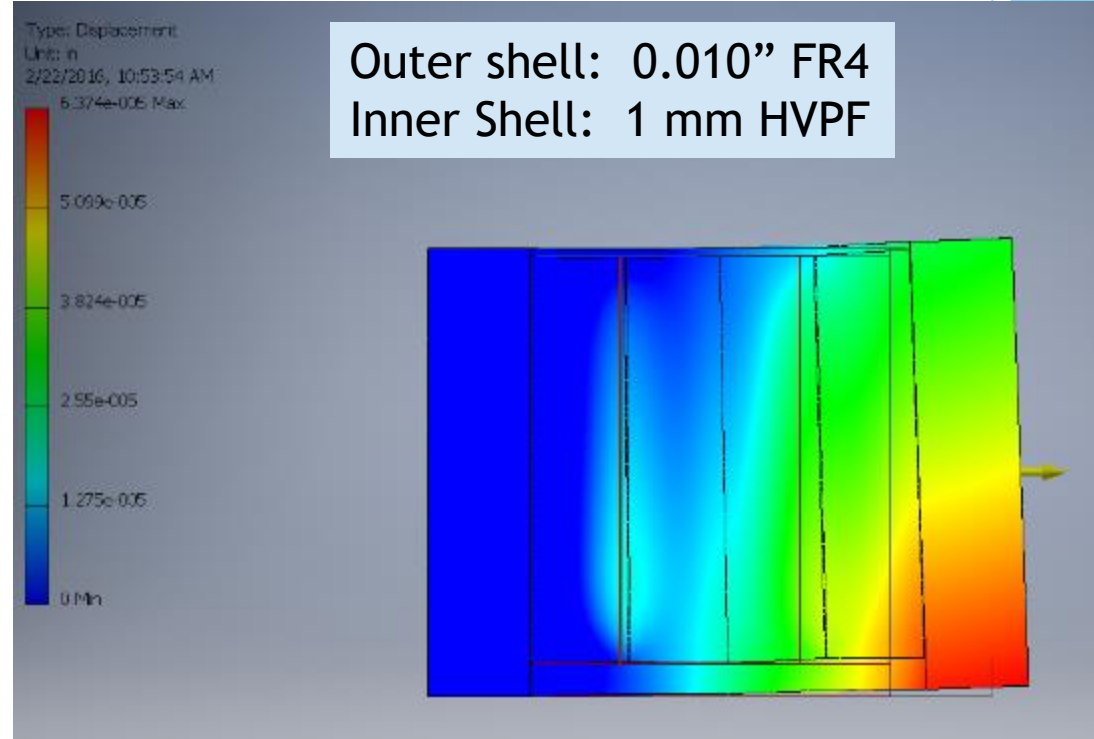
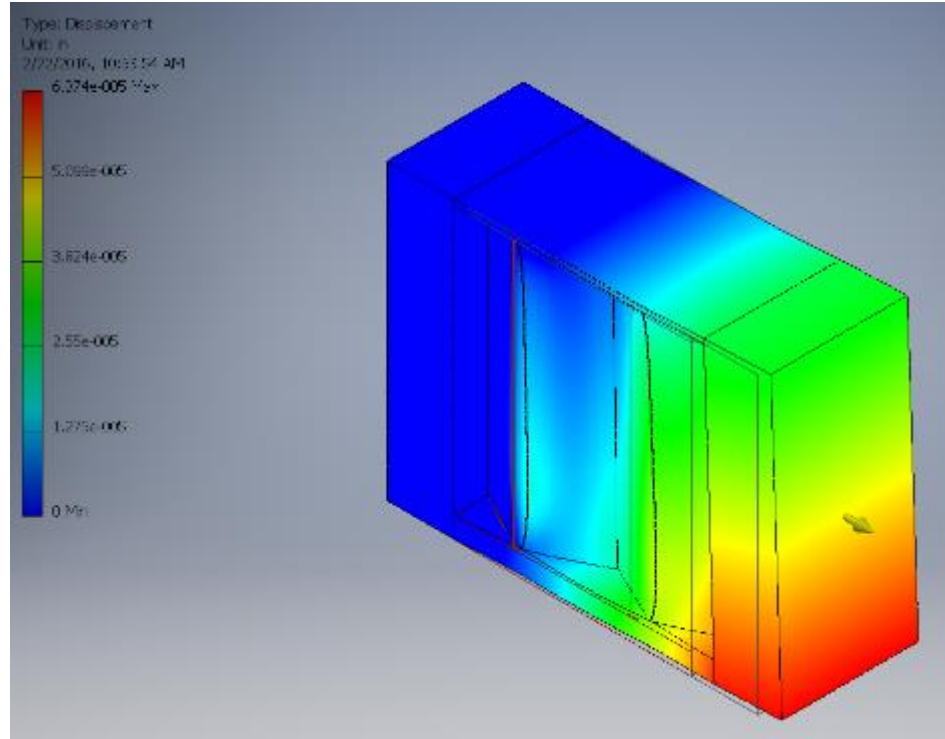
- taking a beam as being defined as having width (b) less than $1/3$ of span (l)



Considering a centre point loaded beam with $b = 0.5m$ and $l = 2m$ and $P = 1500N$

- ▶ Article from a honeycomb manufacturer
- ▶ Analytical calculations of all the moduli.
 - ▶ Option 1:
Use analytical solution to determine input parameters to CAD orthotropic simulations.
 - ▶ Option 2:
Directly compare analytic result to known devices...

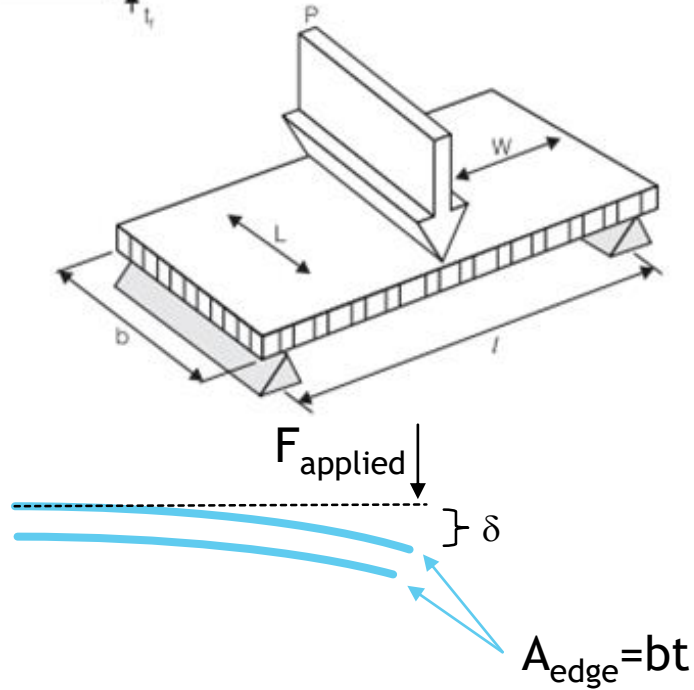
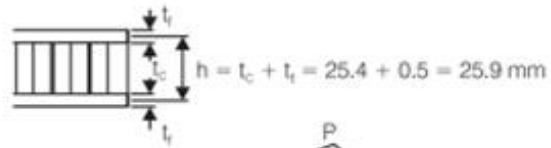
We DID learn something important from “tiny sim”



- ▶ Even though the kapton layer is 1mm thick and the FR4 is 0.010" (.254 mm) thick, the kapton deflects much more under load.
- ▶ We can win in stiffness by layering in some FR4 to the interior electrode surface.
- ▶ This is likely why the ILC folks added a layer of glass cloth to their innermost electrode layer.

Klaus Dehmelt: Mis-matched effective modulus can lead to de-lamination

Engineers remember, physicists forgot...



- Stress results from inner shell getting longer and outer shell getting shorter under load:

$$\frac{F_{stress}}{A_{edge}} = E \frac{\Delta L}{L}$$

- As long as we don't exceed the elastic limit, then the work from the applied force equals the stress work:

$$F_{stress} \Delta L = k F_{applied} \delta$$

- Up to a constant (depending upon load type):

$$\Delta L = h\theta; \quad \delta = L\theta; \quad \Delta L = \frac{h}{L} \delta$$

- Combining Bullet 1&2:

$$Etb \frac{(\Delta L)^2}{L} = k F_{applied} \delta$$

- Plugging Bullet 3 into above:

$$Etb \frac{h^2 \delta^2}{L^3} = k F_{applied} \delta;$$

$$\delta = \frac{k F_{applied} L^3}{Etbh^2}$$

k is unit-less parameter that varies with geometry

Load Types

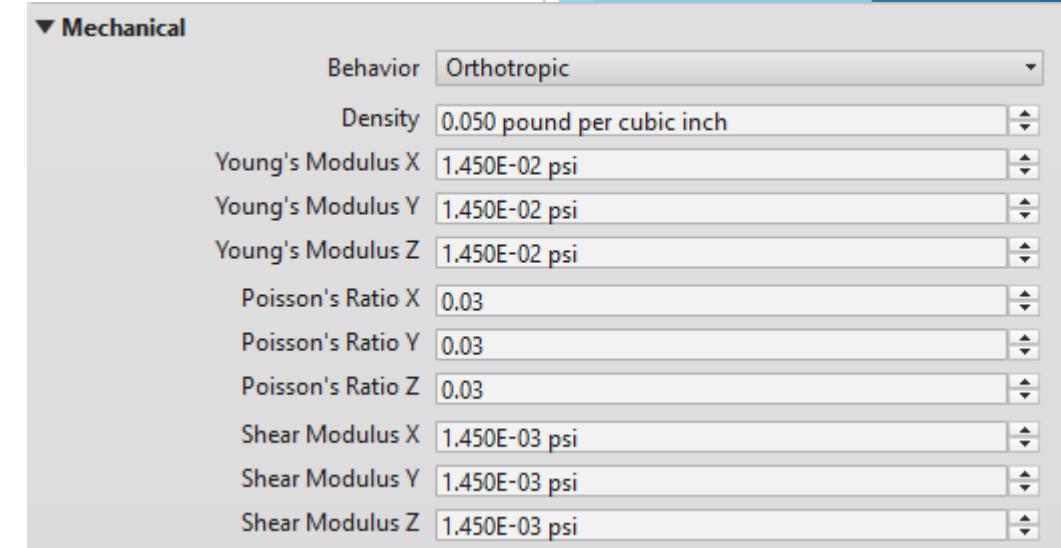
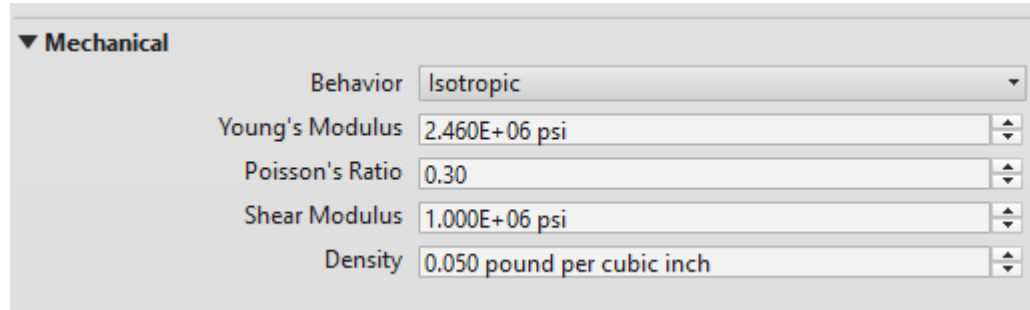
$P = q/b$	Simple Support
	Uniform Load Distribution
$P = q/b$	Both Ends Fixed
	Uniform Load Distribution
P	Simple Support
	Central Load
P	Both Ends Fixed
	Central Load
$P = q/b$	One End Fixed (Cantilever)
	Uniform Load Distribution
P	One End Fixed (Cantilever)
	Load One End
$P = q/b/2$	One End Fixed (Cantilever)
	Triangular Load Distribution

$$\delta = \frac{k P^3}{D}$$

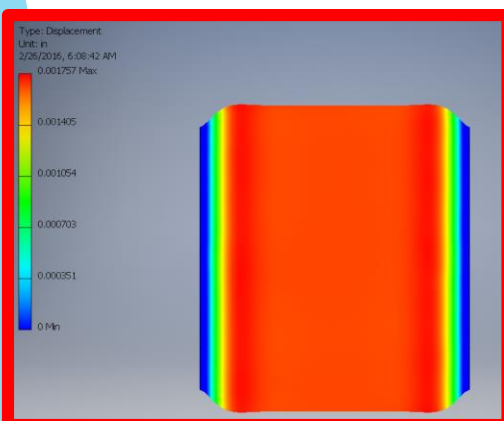
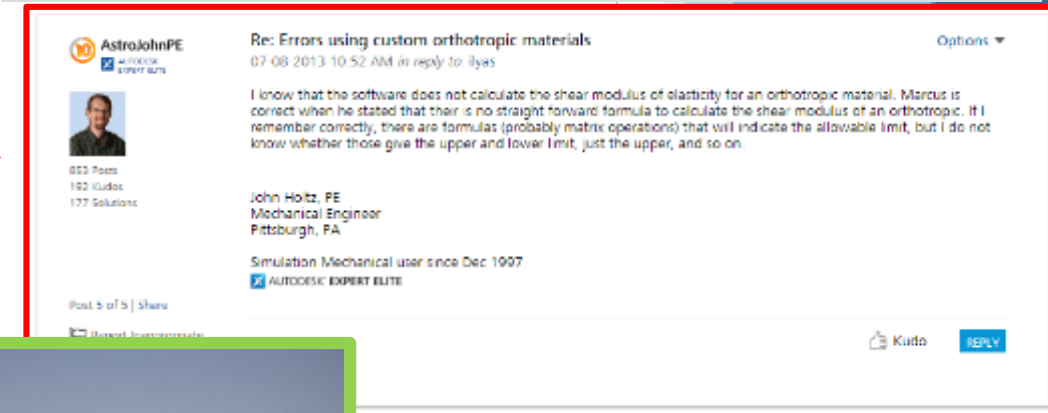
where

$$D = \frac{E_t t_f h^2 b}{2}$$

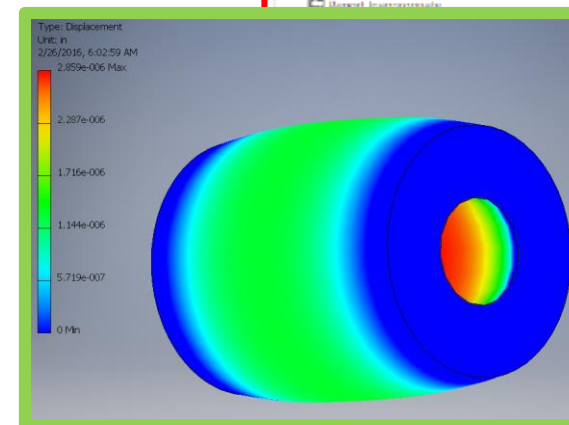
Option 1: AutoDesk Inventor not up to the task...



- ▶ Inventor does indeed have the ability to ENTER the parameters for both isotropic and orthotropic materials.
- ▶ However, we decided to test this:
 - ▶ No matter what parameters we put into the materials, we find that the isotropic parameters are used in the calculation.
 - ▶ Verified by web search...
- ▶ Furthermore, default meshing parameters unhappy with the aspect ratio of our field cage even for isotropic!

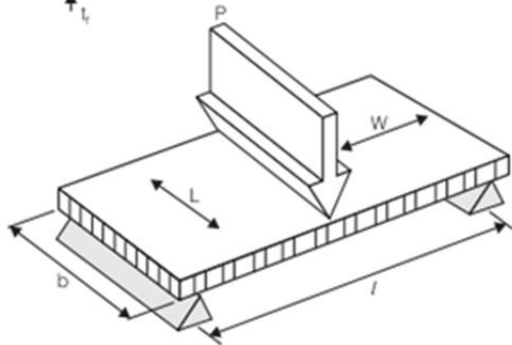
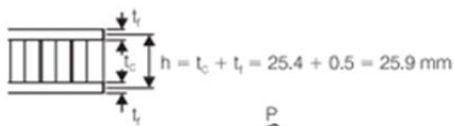


Al cylinder
Real Dimensions
Interior Pressure Sim
Inventor throws warning
Displacement non-physical



Chubby Al cylinder
Interior Pressure Sim
No warnings
Displacement physical

Option 2: Analytical comparison to STAR/ILC



Analytically calculate a simple beam:

- Width = b
- L = <from device>
- Et = <from device>
- h = <from device>

Two conditions:

- Under Pressure (all devices same F_{applied})
- Under gravity (scale using known materials)

NOTE: ALICE publications give too little detail to allow this calculation to be done...

$$\delta = \frac{k F_{\text{applied}} L^3}{E t b h^2} \rightarrow \frac{L^3}{E t h^2}$$

Figure of merit for deflection under pressure

$$\delta = \frac{k F_{\text{applied}} L^3}{E t b h^2} \rightarrow \frac{m_{\text{beam}} L^3}{E t h^2}$$

Figure of merit for deflection under gravity

Sphenix			
Material	density (g/cc)	Length	outer radius (cm)
oFr4	1.85	160	7
Honeycomb	0.064	160	76.97
iFr4	1.85	160	75.70
Kapton	1.42	160	75.6
Total			

STAR - Field Cage			
Material	density (g/cc)	Length	outer radius (cm)
Cu1	8.96	420	200.
Kapton1	1.42	420	200.
Cu2	8.96	420	200.
Honeycomb	0.064	420	200.
Cu3	8.96	420	200.
kapton2	1.42	420	200.
Cu4	8.96	420	200.
Total			

STAR - Containment vessel			
Material	density (g/cc)	Length	outer radius (cm)
Al 1	2.7	420	350.96
Honeycomb	0.064	420	350.76
AL 2	2.7	420	350.16
Total			

ILC			
Material	density (g/cc)	Length	outer radius (cm)
Cu1	8.96	430	4.30E
Kapton 1	1.42	430	4.30E
GRP 1	1.4	430	4.30E
HC	0.064	430	4.30E
GRP 2	1.4	430	4.28E
Kapton 2	1.42	430	4.28E
Cu 2	8.96	430	4.28E
Kapton 3	1.42	430	4.28E
Cu 3	8.96	430	4.28E
Total			

Options:

- ▶ Hemmick dislikes the “strut” design.
- ▶ Threads seem too damned coarse for adjustments at 30 μm flatness spec.
- ▶ With sPHENIX small size we can imagine “turning” the finished end plate to make it VERY flat...

space-frame designs

The ILD endplate **solid model** (previous slides 7 & 8) is modeled in the “equivalent-plate” space-frame design; the separating members are thin plates.

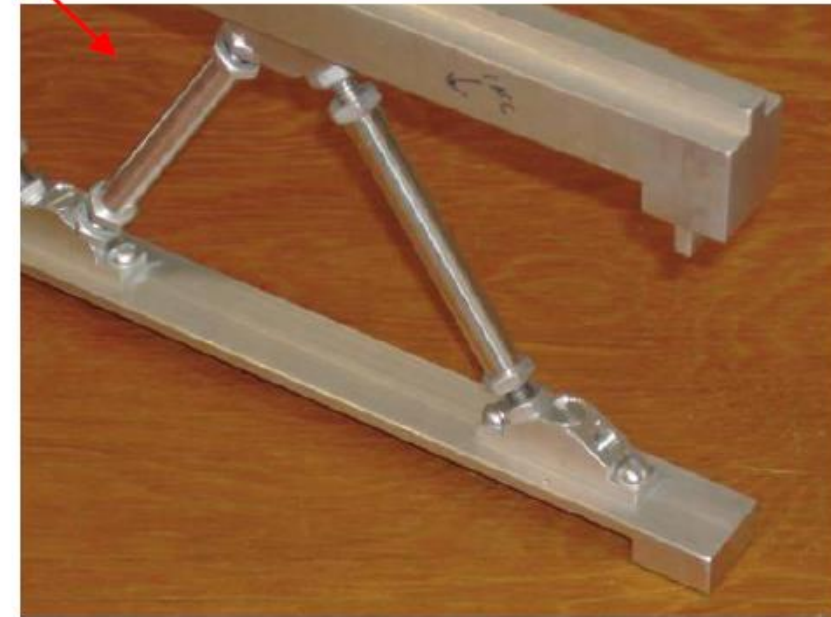
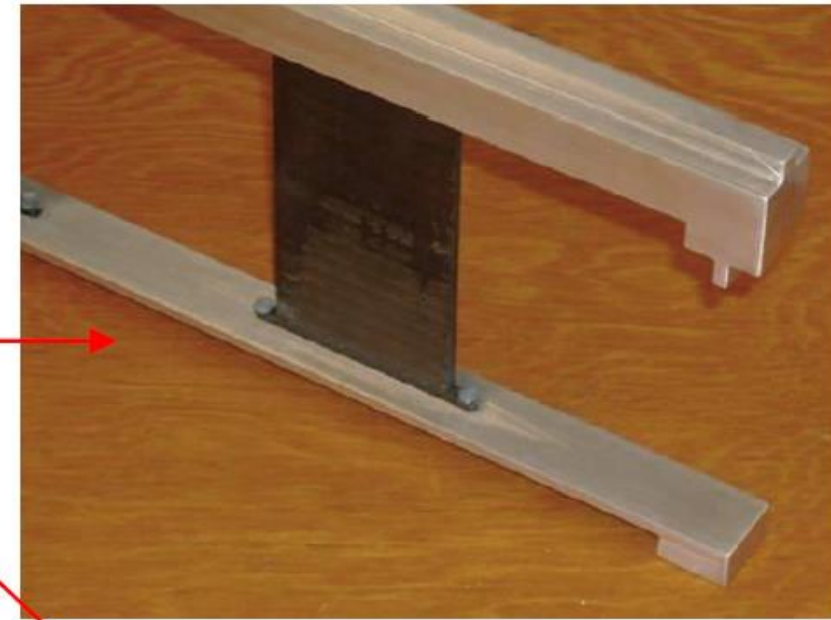
The “strut” space frame design is an alternative.

The thin plate **thickness and width** are adjusted to achieve **rigidity and material equivalent** to a strut design.

The ILD was modeled with equivalent plates only because the struts were too complicated for the FEA.

The final implementation of the ILD endplate may be either the strut or thin plate designs.

A construction design will be discussed.



Validation

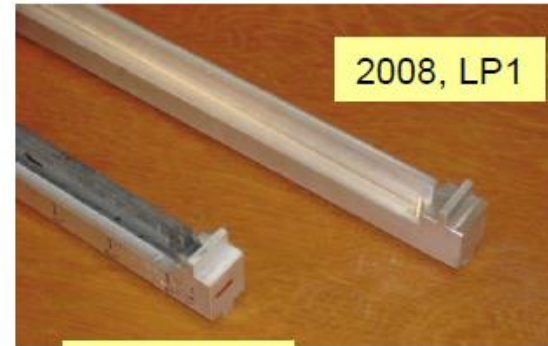
- ▶ Drop the scale of the analysis from full scale to a single beam
- ▶ Measure a real beam to verify that it works

Validation of the FEA with small test beams

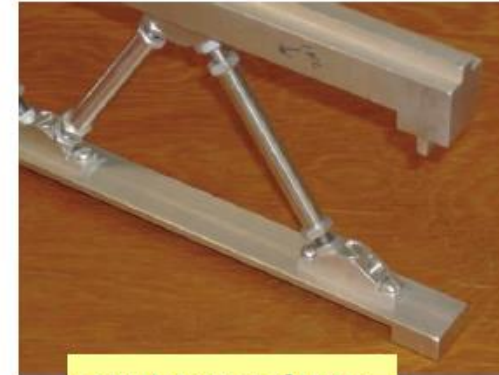
Small test beams represent sections across the diameter of the LP1/LP2 endplate.

For each small test beam, there is a solid model that was used for the FEA.

Deflection of the physical prototypes was compared to the FEA.



Al-C Hybrid



strut space-frame

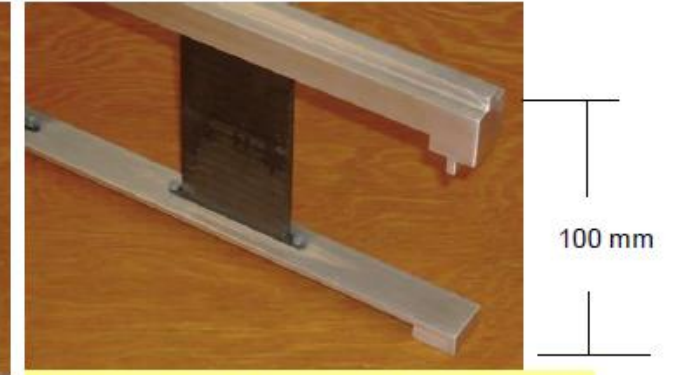
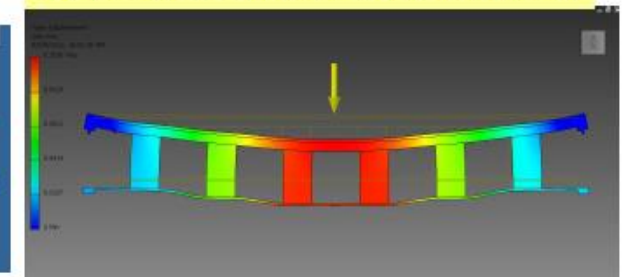
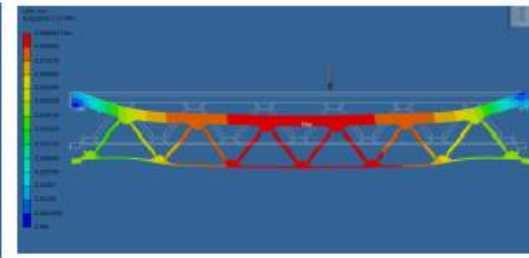
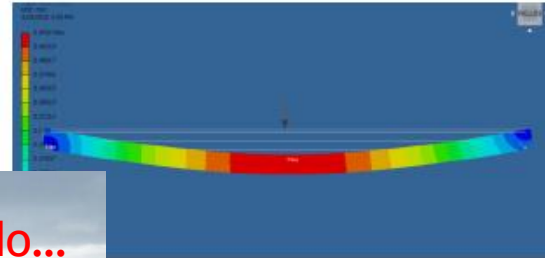
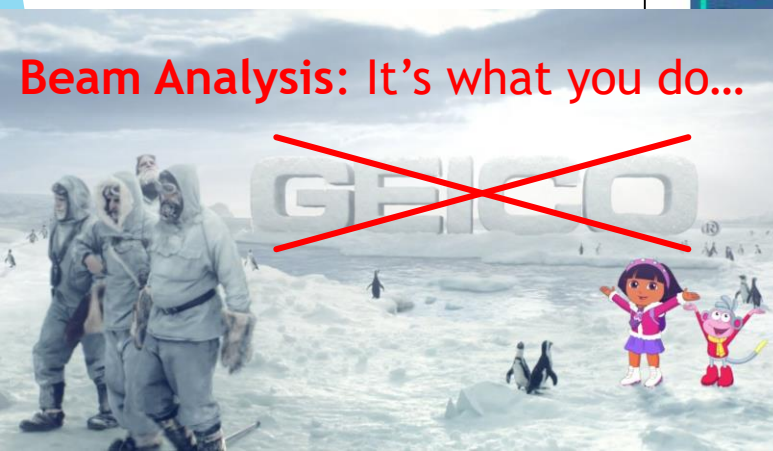


plate space-frame (carbon fiber)



(Carbon fiber material is specified to have the same rigidity as the aluminum and is treated as aluminum in the FEA.)

Deflection measurements of the physical prototypes agree with the FEA.
(presented earlier)



Comparison

- ▶ Because of mechanical size considerations, sPHENIX will have a MUCH easier time meeting deflection specs.
- ▶ Simpler to build designs are actually thinner than the space frame!
- ▶ The concept of going with small modules is also quite a change.

Comparison of deflection for LP1/LP2 endplates: FEA vs. measurements

	mass kg	material %X ₀	calculated deflection μm (100 N)	stress MPa (yield: 241)	measured deflection μm (100 N)
LP1	18.87	16.9	29	1.5	33
LP2 Space-Frame (strut or equivalent plate)	8.38	7.5	23	4.2	27
Lightened	8.93	8.0	68	3.2	
Al-C hybrid (channeled plus fiber)	Al 7.35 C 1.29	7.2	(68-168)	(3.2-4.8)	
Channeled	Al 7.35	6.5	168	4.8	

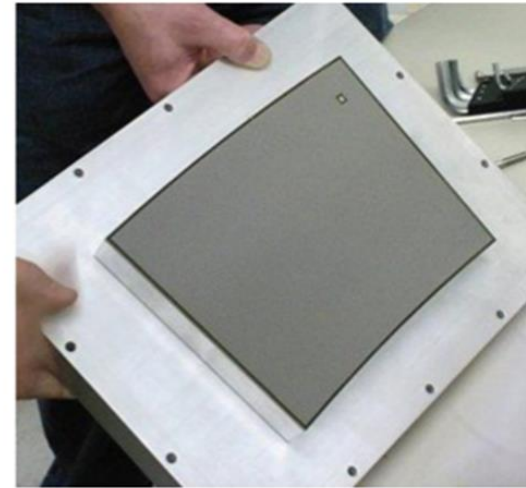
The original LP1 endplate was compared to the FEA earlier.

In both LP1 and LP2, the measured deflection is about 15% higher than from the FEA, which is close for the level of detail of the model.

What is best for us?

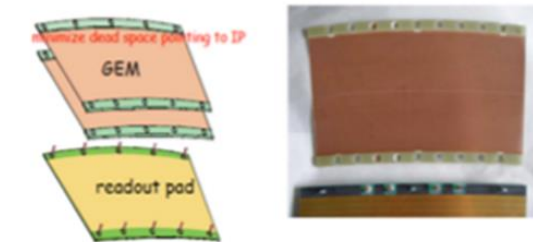
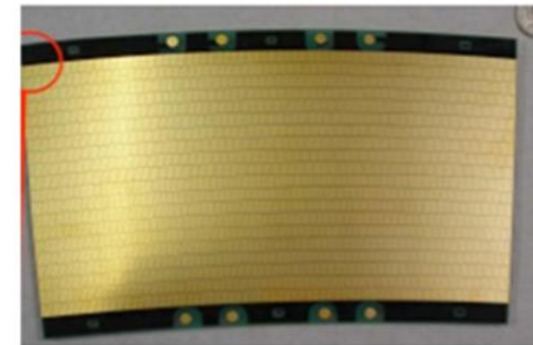
- ▶ The ILD designs whether space frame or other options are all based upon using many smaller modules rather than a few large modules.
- ▶ Advantages:
 - ▶ Less active area impact due to troublesome module; better known GEM technology; easier assembly (by hand); mass spread more uniformly; in-situ module replacement; significantly reduces technical challenges of module design; opens broader vendor availability for GEM and/or μ MEGA production.
- ▶ Disadvantages:
 - ▶ More dead area between modules; field distortion at module edges; mass spread more uniformly; more closely couples the field cage design to module size; more restrictive on electronics readout size.

Micromegas



'Bulk' technology (CERN-Saclay)
with resistive anode (Carleton)

DOUBLE GEM



New 100 micron GEM (plasma-etched
in Japan) stretched from 2 sides.

We need to continue mulling over the options as the best solution is not yet clear.

Drift Velocity

- ▶ Faster drift means that the detector volume clears out faster.
- ▶ Fewer stacked events with v_d large.
- ▶ However, electronics response must be factored in:
 - ▶ SAMPA has 190 nsec peaking time.
 - ▶ Better matched to slow gas for high multiplicity applications.
 - ▶ Makes sense...ALICE uses slow gas.

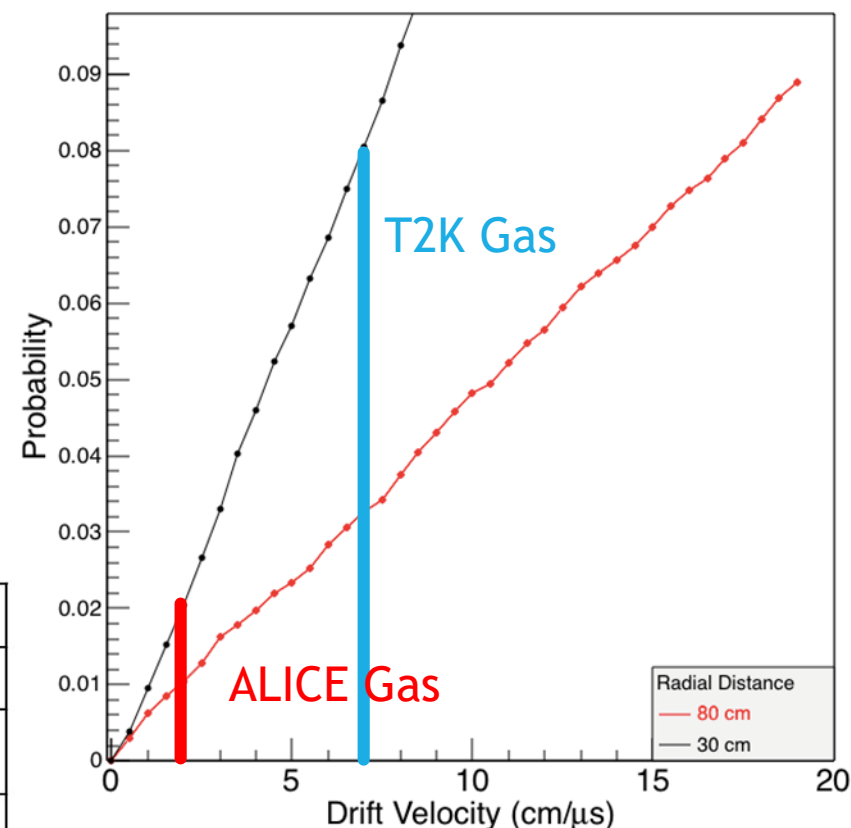
- ▶ Even with ALICE slow gas sPHENIX will experience only between 1-2 stacked events on average.

- ▶ This is because the TPC is so much smaller than ALICE (Typically 5 evts stacked at full luminosity planned for future)

NOTE: A plateau in drift velocity is nice, but ALICE works on the rising edge!

SPECIFICATION	VALUE
Polarity	Pos/Neg
Detector capacitance	18pF - 25pF (TPC) 40pF - 80pF (MCH)
Peaking time	190ns - 300ns
Shaping	4 th order
Sensitivity	12 - 9 - 6 - 3 mV/fC @1V ADC
Linear Range	1V @ 83fC, 110fC, 166fC, 330fC
Power consumption per channel (VDD=1.2V)	< 6mW (PASA: 11mW VDD = 3.3V)
Linearity	< 0.8% @ 12mV/fC

Probability of Overlap Depending on Drift Velocity



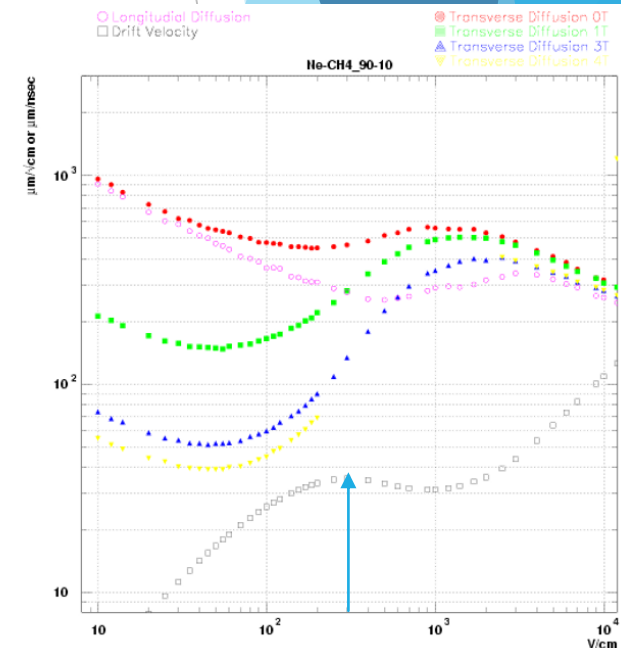
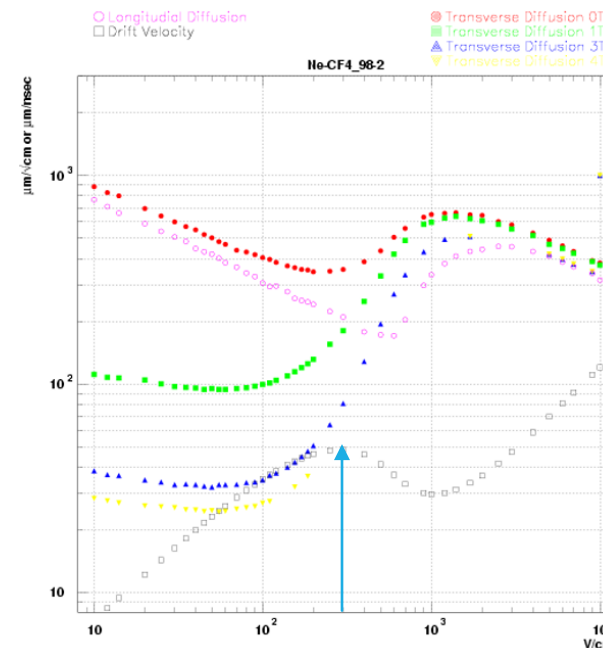
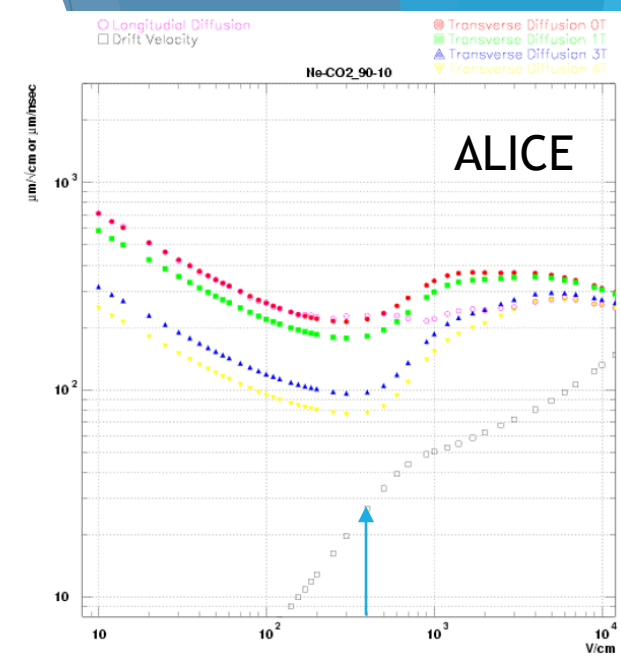
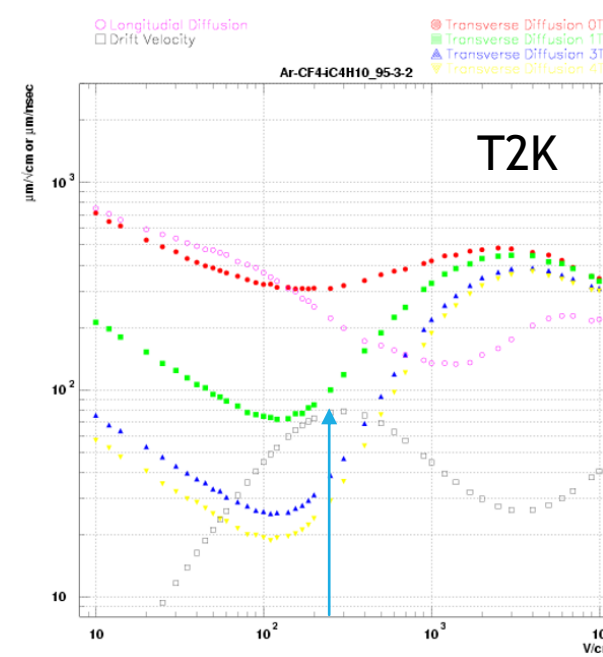
- ▶ “Voxel” occupancy assuming:
 - ▶ 1 degree in phi.
 - ▶ 200 nsec window in zed
- ▶ pCRD
 - ▶ 1.2mm pads; 3 pads per track;
 - ▶ 1.45X better than calculation.

Transverse diffusion

▶ Competing desires:

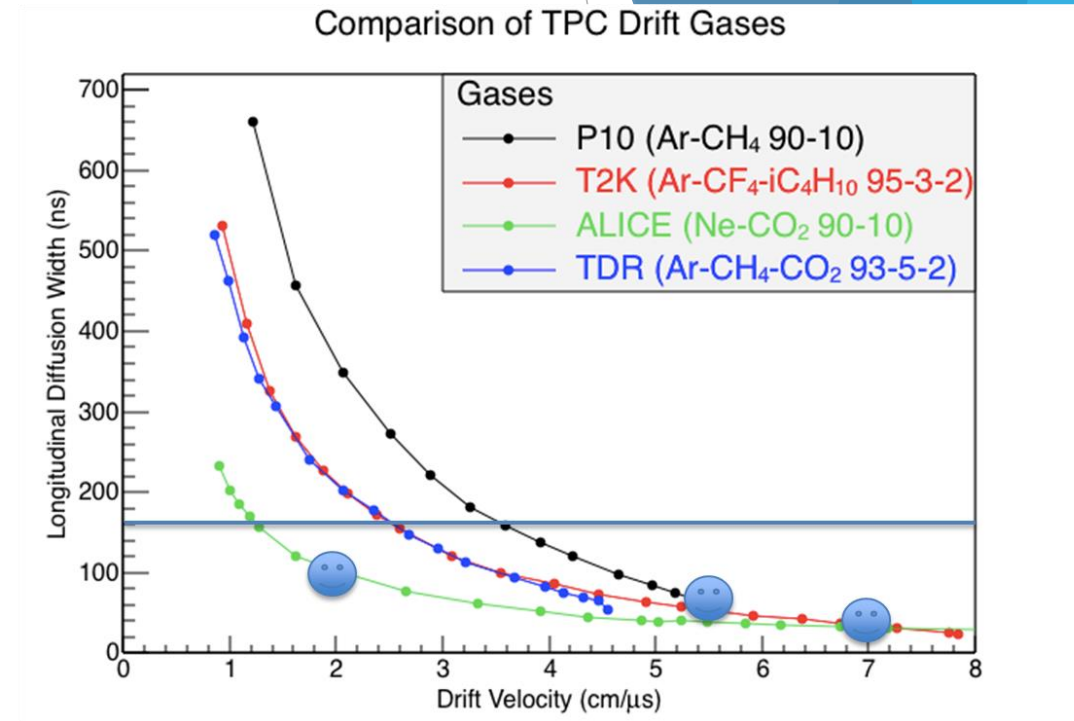
- ▶ Position resolution. Containing charge well in the transverse direction improves position resolution partly through the use of smaller pads.
- ▶ Finite count of pads. To get high resolution you must charge share. Although “patterning” the pads (see talk by Bob Azmoun) allows for charge sharing even with large pads, one must stay within the boundaries of “printable pads”
 - ▶ Minimum feature size ~100 microns.
 - ▶ Limiting feature for electrode points.
- ▶ Diffusion includes not only the drift volume, but the avalanche process that via GEM-Hole-misalignment adds an extra term.
- ▶ Best case:
 - ▶ Small volume diffusion.
 - ▶ Reasonable avalanche diffusion (~500 microns?)

Life is MUCH EASIER for us than ALICE due to smaller pads

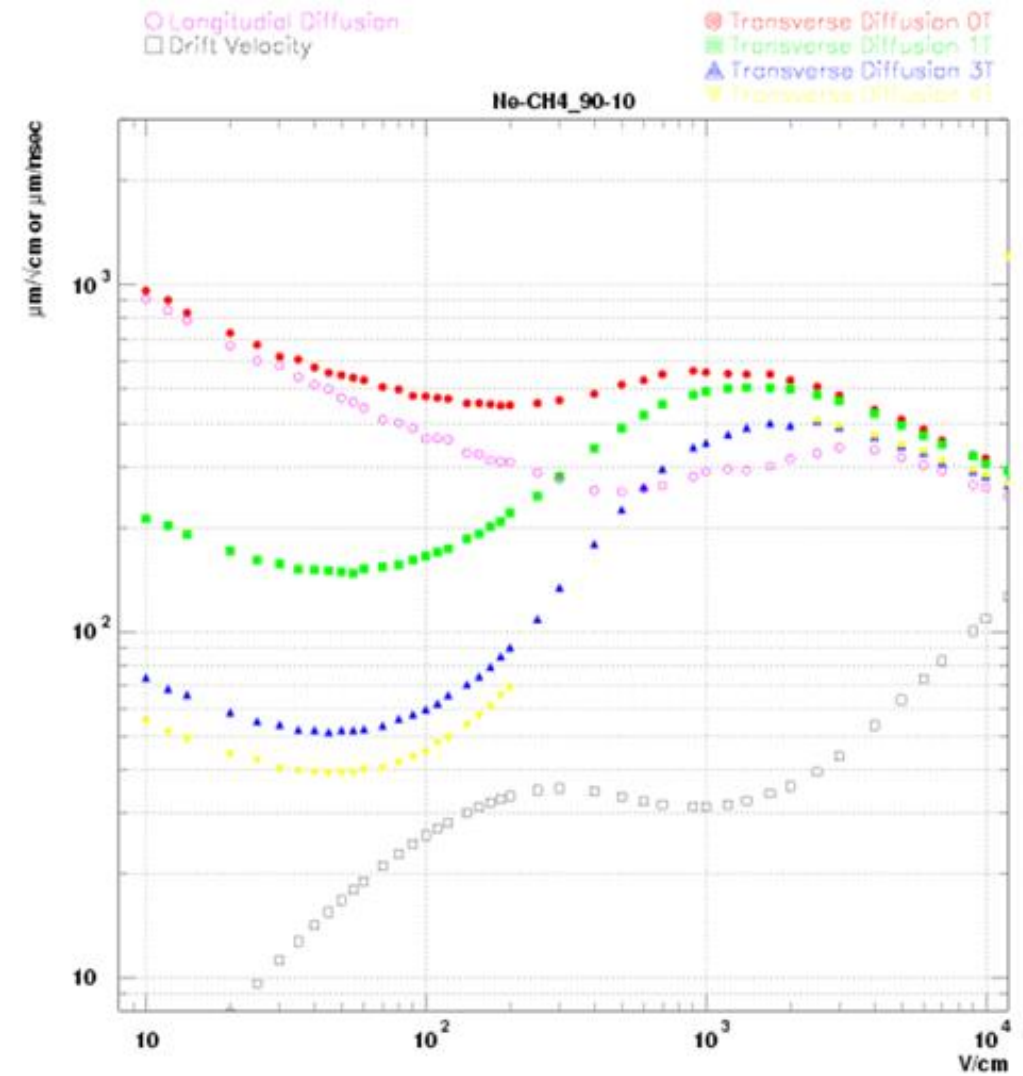
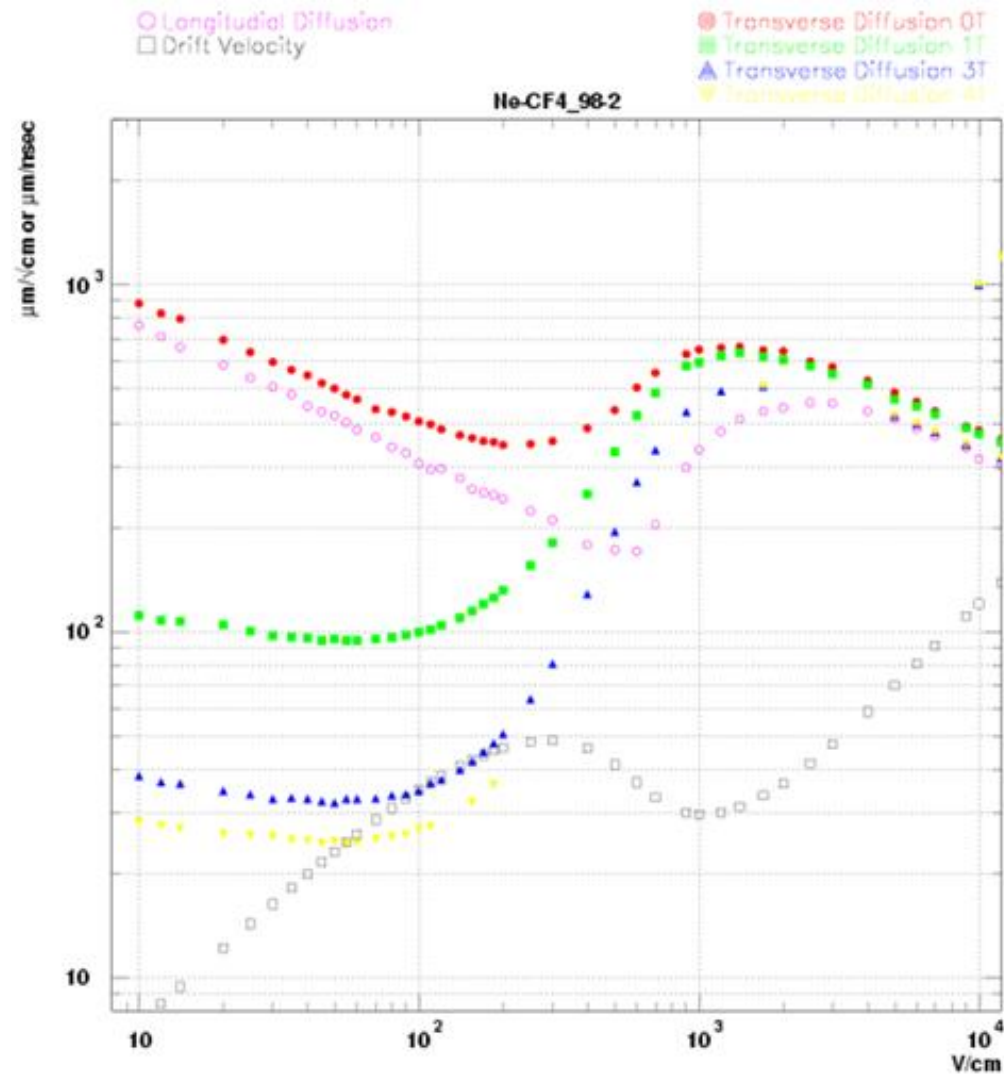


Longitudinal Diffusion

- ▶ Typically longitudinal position resolution is not the limiting factor for tracker resolution.
- ▶ Therefore a diffusion spec should be matched to the shaping time of the electronics to insure linear response of the system for good dE/dx resolution.
- ▶ The line is set to $\sim 2/3$ of the peaking time and the smiley face icons are set to the drift velocity that minimizes transverse diffusion.
- ▶ All these gas choices match well with the SAMPA chip simply because ALICE is designing for slow gas.



Other possible gas choices?



- These are others, but these have a good “gut feeling”. (Neon-based, good diffusion, good plateau)

Aces in the Hole

- ▶ The Baseline sPHENIX program does NOT require dE/dx from the tracker.
- ▶ We can select an operating point that favors low IBF for heavy ion collisions and then regain dE/dx for EIC simply by changing the voltages.
- ▶ We can choose a lower initial ionization gas (already must go to Ne...He is also possible).
- ▶ We can operate using gasses that are more forgiving (Ne CO₂ is NOT on the velocity plateau) of imperfections in temperature/field.
- ▶ We can “hedge” the IBF issue by moving the internal window inward (remember, deflection due to relative space charge).

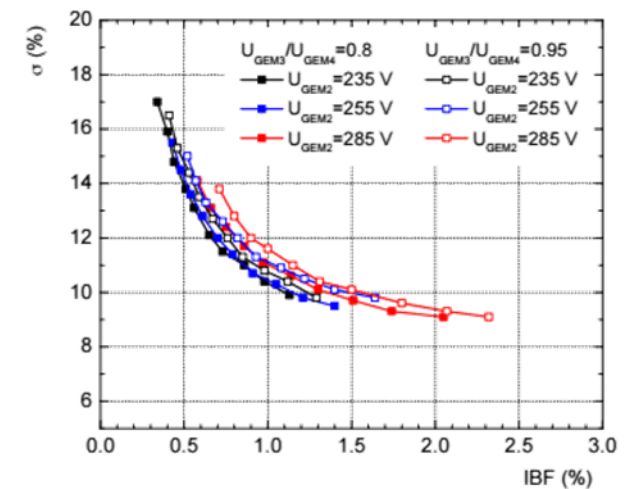


Figure 5.4: Correlation between ion backflow and energy resolution at 5.9 keV in a quadruple S-LP-LP-S GEM in Ne-CO₂-N₂ (90-10-5) for various settings of ΔU_{GEM2} . The voltage on GEM 1 increases for a given setting between 225 and 315 V from left to right. The voltages on GEM 3 and GEM 4 are adjusted to achieve a total effective gain of 2000, while keeping their ratio fixed. The transfer and induction fields are 4, 2, 0.1 and 4 kV/cm, respectively.